THE ATOM: FRIEND OR FOE?

by

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Translated by

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With twenty-two illustrations in half-tone and line diagrams in the text

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Preface

HUMAN beings differ from other animal species by their highly developed intelligence, and especially by their power to foresee events. It is difficult to judge whether the intelligent animals—mammals, birds, social insects—have the faculty of projecting their minds towards the future and of analysing the various combinations of events which might occur. In a sense it could be said that they have to the extent that they take measures to assure their safety. But this could be attributed to ancestral experience, which, by slow adaptation, has enabled the type to determine the best ways of mitigating the numerous dangers to which it is subject. It is only when the group is directly attacked that individuals react strongly and fight to save their dwellings or their young. This is observed, among others, in termites and ants as well as some birds living in communities.

However well armed it may be, there is no animal species which can foresee a danger in the distant future, even less prevent it from occurring.

Man is midway between two states, that of the myopic sheep and a state of high intelligence which will enable him to reason logically. The scientific analysis of the collective behaviour of the human species gives a glimpse of many possibilities, both good and threatening. For centuries it has been reiterated that civilizations are mortal, and that perhaps little is needed to destroy in a few generations marvellous societies which apparently are indestructible. One idea, however, which does not appear to have made any headway in our minds is that humanity as a whole is mortal. As our scientific capacities reach a global scale, it becomes more and more easy to set off the subtle mechanism which will take us all to our doom.

The goat which eats grass by tearing it out with its roots does not know that it is bringing about a fatal chain of events which

may transform into a desert the country in which it is living. From this point of view man has not got any farther than the goat.

We are totally in the dark as to whether some insignificant event in our planetary biophysical history will not set off an irresistible series of profound modifications.

Ecological examples of waste and lack of foresight on a planetary scale are many and do not need to be quoted here. We are all convinced in our innermost beings that the human species, despite its strength and its knowledge, is highly fragile and vulnerable. There are too many links between ourselves and the environment which enables us to live and in which we evolve for there to be any doubt that every variation in this environment will have amplified repercussions on our being.

These few facts should enable us to grasp the grave dangers of the new era we are entering. Nuclear energy is a new problem without precedent for humanity. But we are tackling it as blind and ignorant men.

Blind, because we do not know where nuclear energy in its present form is leading us. The problems of the use of this energy are the same as those with which humanity has had to cope so far: a search for raw materials, battles for spheres of influence, quarrels of prestige and nationalism driven to extremes through false illusions of power. "The atom at the service of mankind" in reality is in danger of being solely at the service of a continuation of the struggles, open or secret, which have shaped the destiny of the world for years.

The energy drawn from the heart of the matter of which we are formed is too precious to become a political instrument. Remember the words of Einstein shortly before his death: "The power set free from the atom has changed everything, except our ways of thought, and we are sliding towards a catastrophe without precedent." This is thrown into bold relief by the fact that since 1945 nuclear weapons have represented a major share of the efforts of the great Powers, despite the large sums devoted in the past few years to exclusively peaceful applications. These applications will, for many years, bear the marks of their warlike antecedents.

Ignorant, too, we said. We know so little by comparison with all that is still unknown! Yet it is from these unknown facts that

tomorrow will be built, and not from what is behind us. To rise, man must make fresh discoveries without ceasing. But so many possibilities are still intact before us. When men speak of the forthcoming shortage of energy, the geophysicists smile because they know all that is contained in the earth, the seas, the winds, and the sun by which we live. The amounts of latent energy around us are enormous, and the technical problems which must be solved to harness them are simpler than those which the atomic physicists solved without too much difficulty.

And the unknown is full of pitfalls in the form of surprising quirks of physical and biological laws. We know very little of the way in which living things will evolve in contact with a more and more radioactive environment. Long and painstaking work will be needed to trace one by one the individual strands which make terrestrial life a prodigious balance between living and inanimate matter.

All this does not mean that nuclear science by itself is of sinister import for ourselves and our progeny. It is not because a child is born amidst evil geniuses that it will necessarily become a harmful being. We must therefore give to nuclear science, this latest-born of human genius, all our solicitude, constant attention, and an enlightened vigilance to turn it into a faithful servant instead of a dangerous despot.

The importance of the consequences implied by nuclear energy for the development of our civilization compels us to adopt new attitudes.

This nuclear future can be a new era for man, but he will have to acquire a world conscience if he wants to survive. We must evolve a new concept of civilization, in which science can progress only when based on human considerations, and in which the horrors of nuclear conflict make war between men inconceivable if not impossible.

We can master the atom, but this is of no use if we are not firstly masters of ourselves. Great treasures of philosophy and wisdom lie dormant in our civilization; it is high time that we turned to them and allied them with science.

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Preliminary Notes

HIGHLY technical terms are avoided in this work, which is aimed at as wide a public as possible. Nevertheless, certain terms, which are in any case widely known, must be and are used very frequently in these pages—for example, fission, radioactivity, isotope, and curie.

The reader will, therefore, find here a small glossary of these terms to which he may refer if their meaning should escape his memory.

General facts about atomic theory, nuclear physics, fission, and fusion are explained at length in the first four chapters.

Element. This is the name given to a chemically individual unit of matter: hydrogen, uranium, gold, copper, oxygen, nitrogen, and plutonium are elements. Of these, 90 are found in nature, two are absent in this classification and have been synthesized by nuclear science, while 11 others—called trans-uranic elements because their atomic number is higher than that of uranium—have also been synthesized by nuclear science. Of the 90 natural elements, 81 are stable, and the other nine naturally radioactive elements (see Chapter 1).

Atom. The smallest material particle of a given element, measuring a hundred-millionth (1/100,000,000) of a centimetre in diameter, and weighing, in grammes, a number so small that twenty-two noughts must be placed after the decimal point to write it. Atoms are made of electrons orbiting around a central nucleus.

Molecule. A group of atoms, chemically linked, which is a basic unit of any substance. Water is an agglomeration of a prodigious number of molecules, each composed of two atoms of hydrogen and one atom of oxygen. Cellulose, rubber, urea, table salt, and

chlorophyll are all molecules containing from a few to several thousand atoms.

Electron. An infinitesimal atomic particle carrying a unit electrical charge, and having a diameter one ten-million-millionth (1/10,000,000,000,000) of a centimetre, which orbits round a positively charged centre called the nucleus of the atom. Electricity is a flux of electrons.

Nucleus. The condensation of matter at the core of the atom, carrying a positive charge, around which the electrons gravitate. Nuclear energy is derived from this core.

Neutron. A 'heavy' particle, electrically neutral, which with the proton is a constituent of atomic nuclei. Free neutrons cause the fission (or splitting) of the nuclei of the heavy elements such as uranium-235.

Proton. A 'heavy' particle carrying a positive unit electrical charge which is a constituent of the nucleus. There are as many protons as electrons in a neutral atom.

Atomic Number (*Z*). This is the number assigned to each element by its chemical classification. It is equal to the number of electrons of the atom and to the number of protons in its nucleus. The atomic number of carbon is 6, and that of uranium is 92.

Mass Number (*A*). This is the total number of protons and neutrons in a given nucleus, and is so named because virtually all the mass, or weight, of an atom resides in its nucleus. For example, carbon-14, which is element number 6, has six protons and eight neutrons, hence the mass number 14. Uranium-235 (uranium being element number 92) has 92 protons and 143 neutrons: $92+143=235$.

Isotope. This is the name given to varieties of an atom belonging to the same *chemical* type but differing *physically*. It is defined by the atomic number and by the mass number. Carbon-14 is an isotope of carbon which has other isotopes—for example, carbon-12 (six neutrons and six protons). Uranium-235 is one isotope of uranium, U-238 is another. Plutonium-239 is an isotope whose nucleus has 94 protons and 145 neutrons. Since an element can be defined by the number of its protons, it follows that its isotopes vary only according to the number of neutrons in their nuclei. There are 275 stable isotopes of the 90 elements found in nature.

Radioactivity. This is the expulsion by a nucleus which has an excess of energy of one or more particles, or of energy in the

form of radiation (electromagnetic waves). There are three forms:

Alpha-activity. The expulsion of a group of two protons and two neutrons: this is a helium nucleus or alpha particle.

Beta-activity. The expulsion of a negative or a positive electron from the nucleus. The capture by the nucleus of one of the orbiting (negative) electrons is equivalent to the emission of positive beta radiation.

Gamma-activity. This is the emission of ultra-short wave electromagnetic radiation.

More than 1300 radioactive isotopes of the 103 known elements have been identified.

MeV. The unity of energy applied to the radioactive emission of particles or radiation. It is the abbreviation of 'million electron-volts.' The fission of a uranium nucleus produces some 200 MeV. A neutron must have an energy of 3 MeV or more to split a uranium-238 nucleus. Cobalt-60 emits two gamma rays, of 1·17 and 1·33 MeV. One MeV is about equal to one-millionth of an erg, which is the work done in displacing a mass of one gramme for a distance of one centimetre.

Half-life. The time taken for the activity of a radioactive substance to decay to half its original value, or for half the atoms present to be transmuted by radioactive decay into other substances. For example, of four grammes of radium-226, only two will remain 1600 years hence, and after a further 1600 years only one. This period of 1600 years is thus called the half-life of radium-226. All radioactive substances have half-lives. That of strontium-90 is 28 years; that of plutonium-239 is 24,000 years; and that of iodine-131 is eight days. Uranium-238 and thorium-232, with 4,500,000,000 and 10,000,000,000 years, respectively, account for the presence in nature of nine radioactive elements (numbers 84 to 92) formed by their disintegration. There is also a biological half-life, by definition the time taken to eliminate half a chemical compound or an isotope from the human body. For example, the biological half-life of cobalt-60 in the body is eight days. This is because after eight days half any amount of ingested cobalt will have been excreted, after a further eight days half the remainder, and so on. This has nothing to do with the radioactive half-life, that of cobalt-60 being 5·2 years.

Fission. The breaking up of a heavy nucleus caused by the

impact of a nuclear particle—a neutron, for example. Fission liberates nuclear energy.

Fusion. The combination, or fusing together, of the nuclei of light or simple elements. This process also liberates nuclear energy.

Thermonuclear. A term applied to fusion processes because they demand extremely rapid movement of the reacting particles, this movement being expressed as a temperature.

Ions, Ionization. Electrical imbalance compared with the neutral state, caused by the loss by an atom of one or more of its electrons. Alpha and beta particles cause intense ionization in matter which they penetrate by the electrical disturbance along their tracks. Gamma radiation also has an ionizing effect, albeit indirectly; hence the harmful biological effects of nuclear radiations which penetrate or pass through living tissue.

Activity. The activity of a radioactive source is the number of atomic disintegrations in it over a given period of time and is expressed in units called curies.

Curie. The exact meaning of this unit must be understood fully to appreciate many aspects of present-day nuclear events.

The curie is the number of disintegrations each second in a gramme of radium—that is, 37,000,000,000. For example, when a 20-kiloton (20,000 tons of TNT) atomic bomb explodes, the radioactivity of the mushroom cloud one minute after the explosion is equivalent to that of 820,000 tons of radium. In curies it can be expressed as $820{,}000 \times 1{,}000{,}000$, and the number of disintegrations per second in the mushroom at that moment as $820{,}000 \times 1{,}000{,}000 \times 37{,}000{,}000{,}000$. One hundred years after the explosion, the activity of the remains of this cloud spread around the world is still 600 curies, or 22,200,000,000,000 disintegrations per second.

Often the radioactive content of living matter is expressed in micromicrocuries. For example, strontium-90 behaves in the human body almost exactly like calcium, as we shall see later. It is thus important to know how much strontium is mixed with the calcium of bones. This is expressed in micromicrocuries of strontium per gramme of calcium, or a Sr Unit. Caesium-137 body content is expressed in units of micromicrocuries of caesium per gramme of potassium. 'Micromicro' is a millionth of a millionth, and since the curie corresponds to 37,000,000,000

disintegrations per second, the micromicrocurie will correspond to 2·22 disintegrations per minute. For example, to say that the average content of strontium-90 in human bone in the United States during 1958 was 0·20 Sr Units means that each gramme of the bone calcium contained enough strontium-90 to give 0·44 disintegrations each minute. And, as a man weighing 76 kilogrammes will have a skeletal content of around 1000 grammes of calcium, this would mean a total of 440 disintegrations per minute from the whole of the skeleton and the teeth.

I have used certain other specialized terms:

Metabolism. This covers the range of chemical functions which maintain life.

Biosphere. This is the thin terrestrial layer where life flourishes.

Fall-out. The rapid or slow descent of dusts and rain which bring down to earth the radioactive remnants of atomic explosions.

Troposphere. Air from sea-level to 6–7½ miles altitude.

Stratosphere. Rarefied air from 7½ miles to 30 miles.

Kiloton and Megaton. See pp. 122–123.

(*n*, gamma). This notation describes a nuclear reaction in which the capture of a neutron is followed by the emission of radiation. The isotope (Z, A) to which this happens thus becomes $(Z, A+1)$.

(*n*, 2*n*). This describes in shorthand a reaction where a nucleus captures a neutron, but later emits two neutrons. The isotope to which this happens (Z, A) becomes $(Z, A-1)$.

Kilowatt (kW). This is a unit of power, not to be confused with kilowatt-hour (kWh), a unit of energy. If a power-station of a capacity of 100,000 kilowatts works at full power for a year, it will produce an energy of $100{,}000 \times 8760$ kilowatt-hours, since there are 8760 hours in a year.

Röntgen. This is a unit used to measure the amount of X-rays or gamma radiation received by the body. Currently, the maximum dose tolerated amounts to 0·3 röntgens per week. A whole-body dose of 400 röntgens would result in the deaths of half the people receiving it. Some insects can survive 12,000 röntgens.

Rad. The unit of absorbed ionizing radiation dose. One rad is equal to an energy absorption of 100 ergs per gramme of tissue.

PART I: INTRODUCTORY

I

Elements and Atoms

THIS chapter is designed to explain as clearly as possible the essential principles of atomic theory which all educated men should understand.

Far from being obscure or abstruse, nuclear science, on the contrary, represents a great simplification in our concept of the world. But, instead of following the work of the scientists through the centuries, we are able, in an explanation such as this, to telescope several stages, and draw a rapid overall picture of the synthesis patiently built up by much famous, and also much unrecognized, labour.

THE CHEMICAL ELEMENTS

There are 92 elements in nature.[1] To these are now added 11 transuranic elements created by man since 1940. The 92 are listed from number 1—hydrogen—to number 92—uranium. After this number, the 11 other elements are called transuranic, since they fall beyond the limit fixed by the chemists 20 years ago at uranium.

The following table lists the chemical elements arranged according to the complexity of their structure. First comes the atomic number, then the name of the element and its chemical symbol—a shorthand notation used by chemists which usually contains one or more letters of the element's name—then the origin of the name and the date of discovery.

Better than pages of explanations, this table reflects the long and patient trail-breaking by men of science towards the ultimate analysis of matter. The names of the elements, often

1. In actual fact, elements numbers 43 and 61 have never been found in nature but have been synthesized by nuclear processes. They are radioactive elements with a relatively short geological life.

charming, sometimes curious, tell the story of the hopes, the difficulties, and the beliefs of an impressive succession of scientists.

Number	*Name*	*Symbol*	*Origin of Name*	*Date of Discovery*
1	Hydrogen	H	Greek—*hydros-genos* = which forms water	1766
2	Helium	He	Greek—*helios* = sun	1868–95
3	Lithium	Li	Greek—*lithos* = stone	1877
4	Beryllium (Glucinium)	Be	Beryl = precious stone	1797
5	Boron	B	Arabic—*borak* = white	1808
6	Carbon	C	Latin—*carbo* = coal	Prehistory
7	Nitrogen	N	Latin—*nitrum* = saltpetre	1772
8	Oxygen	O	Greek—*oxys-genos* = which forms acid	1774
9	Fluorine	F	Latin—*fluere* = to flow	1886
10	Neon	Ne	Greek—*neos* = new	1898
11	Sodium	Na[2]	Etymology unknown	1807
12	Magnesium	Mg	Magnesia is a district in Thessaly, Greece	1808
13	Aluminium	Al	Latin—*alumen* = alum	1827
14	Silicon	Si	Latin—*silex* = sand	1810–25
15	Phosphorus	P	Greek—*phos-phoros* = which carries light	1669
16	Sulphur	S	Latin—*sulfur*	Prehistory
17	Chlorine	Cl	Greek—*chloros* = green	1774
18	Argon	Ar	Greek—*argon* = inactive	1894
19	Potassium	K[3]	German or Dutch—*pot-assche* = pot ashes	1807
20	Calcium	Ca	Latin—*calx* = quicklime	1808
21	Scandium	Sc	From Scandinavia	1879
22	Titanium	Ti	From Titans, mythological sons of heaven and earth	1791–1857
23	Vanadium	V	From Vanadis, a Scandinavian divinity	1830
24	Chromium	Cr	Greek—*chroma* = colour	1797
25	Manganese	Mn	Latin—*magnes* = magnet	1774
26	Iron	Fe[4]	Old Germanic word	Prehistory
27	Cobalt	Co	German—*kobold* = goblin	1735
28	Nickel	Ni	German—*nickel* = demon	1751
29	Copper	Cu	Latin—*aes Cuprum* = Cyprian brass	Prehistory
30	Zinc	Zn	Etymology doubtful	16th cen.
31	Gallium	Ga	Latin—*Gallia* = France	1875
32	Germanium	Ge	Latin—*Germania* = Germany	1886
33	Arsenic	As	Arabic—*az-zernik* = orpiment, arsenic trisulphide	1250

2. Na comes from Arabic—*natroum* = sodium carbonate.
3. K comes from Latin—*kalium* = pot ashes.
4. Fe comes from Latin—*ferrum* = iron.

Number	*Name*	*Symbol*	*Origin of Name*	*Date of Discovery*
34	Selenium	Se	Greek—*selene*=moon	1817
35	Bromine	Br	Greek—*bromos*=stench	1826
36	Krypton	Kr	Greek—*krypton*=hidden	1898
37	Rubidium	Rb	Latin—*rubidius*=deep red	1861
38	Strontium	Sr	From Strontian, in Argyll	1790
39	Yttrium	Yt	From Ytterby, Swedish town	1794–1828
40	Zirconium	Zr	Arabic—*zargun*=golden colour	1824
41	Niobium (Columbium)	Nb	Greek—Niobe a daughter of Tantalus . . . niobium found in association with tantalum	1801
42	Molybdenum	Mo	Greek—*molybdos*=lead	1782
43	Technetium[5]	Tc	Greek—*techne*=artifact	1937
44	Ruthenium	Ru	Latin—*Ruthenia*=area in Russia	1844
45	Rhodium	Rh	Greek—*rhodon*=rose	1803
46	Palladium	Pd	From Pallas, one of the asteroids	1803
47	Silver	Ag[6]	Germanic origin, etymology doubtful	Prehistory
48	Cadmium	Cd	Greek—*kadmia*=an earth	1817
49	Indium	In	From its indigo blue spectrum	1863
50	Tin	Sn[7]	Anglo-Saxon—tin	Prehistory
51	Antimony	Sb[8]	Latin—*antimonium* also reputed to be derived from *anti-moine* (French) anti-monk, because of its harmful effects on the monastery chemists of the Middle Ages	Prehistory
52	Tellurium	Te	Latin—*tellus*=the earth	1782–98
53	Iodine	I	Greek—*iodes*=violet	1811
54	Xenon	Xe	Greek—*xenos*=stranger	1898
55	Caesium	Cs	Latin—*caesium*=sky blue, from its spectrum	1860
56	Barium	Ba	Greek—*barys*=heavy	1774–1808
57	Lanthanum	La	Greek—*lanthano*=to lie hidden, with reference to the lateness of its discovery	1839
58	Cerium	Ce	From Ceres, Latin goddess of harvests	1803
59	Praseo-dymium	Pr	Greek—*prasinos*=green and *didymos*=twin	1885
60	Neodymium	Nd	Greek—*neos*=new, and *didymos*=twin	1885
61	Promethium[9]	Pm	From Prometheus, Greek demi-god who stole fire from Olympus for the use of mankind	1944

5. This radioactive element does not exist in nature.
6. Ag comes from the Latin—*argentum*.
7. Sn comes from the Latin—*stannum*.
8. Sb comes from the Latin—*stibium*.
9. This is another artificial radioactive element.

Number	*Name*	*Symbol*	*Origin of Name*	*Date of Discovery*
62	Samarium	Sm	From Samarski, Russian mining official	1879
63	Europium	Eu	Latin—Europe	1901
64	Gadolinium	Gd	From Gadolin, Swedish geologist	1880
65	Terbium	Tb	From Ytterby, Swedish town	1843
66	Dysprosium	Dy	Greek—*dysprositos*=hard to get at	1886
67	Holmium	Ho	From *Holmia*, the ancient name for Stockholm	1879
68	Erbium	Er	From Ytterby, Swedish town	1843
69	Thulium	Tm	From Thule, Latin name for some land north of Britain	1880
70	Ytterbium	Yb	From Ytterby, Swedish town	1878
71	Lutetium	Lu	Latin—*Lutetia*=Paris	1907
72	Hafnium	Hf	From *Hafnia*, ancient name for Copenhagen	1923
73	Tantalum	Ta	From Tantalus, mythological King of Lydia condemned to endless tortures by the gods, and the fact that tantalum was a very difficult substance to isolate	1802
74	Tungsten	W[10]	Swedish—*tung-sten*=heavy stone	1783
75	Rhenium	Re	Latin—*Rhenus*=Rhine	1925
76	Osmium	Os	Greek—*osme*=smell, from pungent odour of one of its compounds	1803
77	Iridium	Ir	Greek—*iris*=rainbow	1803
78	Platinum	Pt	Spanish—*platina*=little silver	1750–1838
79	Gold	Au[11]	Ancient Germanic word	Prehistory
80	Mercury	Hg[12]	Roman god—messenger of the gods	Prehistory
81	Thallium	Tl	Greek—*thallos*=budding branch, from green line in spectrum	1861
82	Lead	Pb[13]	Anglo-Saxon word	Prehistory
83	Bismuth	Bi	German—*wismut*—*weisse masse*=white mass	15th century
84	Polonium	Po	Poland was Marie Curie's country of birth	1898
85	Astatine	At	Greek—*astatos*=unstable	1940
86	Radon	Rn	From radium	1900
87	Francium	Fr	From France	1939
88	Radium	Ra	Latin—*radius*=ray	1898
89	Actinium	Ac	Greek—*aktinos*=ray	1899
90	Thorium	Th	From Thor, Scandinavian god	1828

10. W from German *wolfram*, a tungsten-bearing mineral.
11. Au from Latin—*aurum*.
12. Hg from Greek—*hydrargyrum*=liquid silver.
13. Pb from Latin—*plumbum*=lead.

Number	*Name*	*Symbol*	*Origin of Name*	*Date of Discovery*
91	Protoactinium	Pa	Greek—*protos aktinos* = first ray	1917
92	Uranium	U	Uranus, the 7th planet	1789–1841
93	Neptunium	Np	Neptune, the 8th planet	1940
94	Plutonium	Pu	Pluto, the 9th planet	1940
95	Americium	Am	From America	1945
96	Curium	Cm	From Pierre and Marie Curie	1945
97	Berkelium	Bk	From Berkeley, Californian research centre	1950
98	Californium	Cf	From California	1950
99	Einsteinium	Es	From Albert Einstein	1952
100	Fermium	Fm	From Enrico Fermi	1952
101	Mendelevium	Md	From Dimitri Mendeleev	1955
102	Nobelium[14]	No	From Alfred Nobel	1958
103	Lawrencium[15]	Lw	From Lawrence Radiation Laboratory (U.S.)	1961

14. The actual production of nobelium is contested in some scientific circles.

15. Lawrencium was first detected on February 14 but the official announcement was made on April 12.

This table brings some interesting facts to our attention. We see that only a few elements were extracted and used by man in prehistoric times—iron, copper, silver, and lead, among others. Most of the other elements were separated by the chemists during the last two centuries mainly, at the beginning of the period which saw the birth and development of chemistry.

An immense step forward was made by the Russian chemist, Mendeleev, around 1870. He put forward a logical classification of the 60 or so elements then known. His starting point was the fact that certain elements, at that time called 'simple substances,' behave in the same kind of way. In other words, chemical compounds formed by such elements with other elements in turn have the same type of structure. For example, sodium joins with chlorine to form NaCl, which we all know since it is common salt. But potassium links up with chlorine in the same way and in the same proportions to form a molecule[16] of potassium chloride KCl. In modern terminology we say that an atom of Na or an atom of K combine with an atom of Cl to form a molecule of NaCl or KCl.

More than a million different molecules are now known. Some, in inorganic chemistry, are very simple like NaCl or H_2O

16. A molecule results from the chemical combination of several atoms.

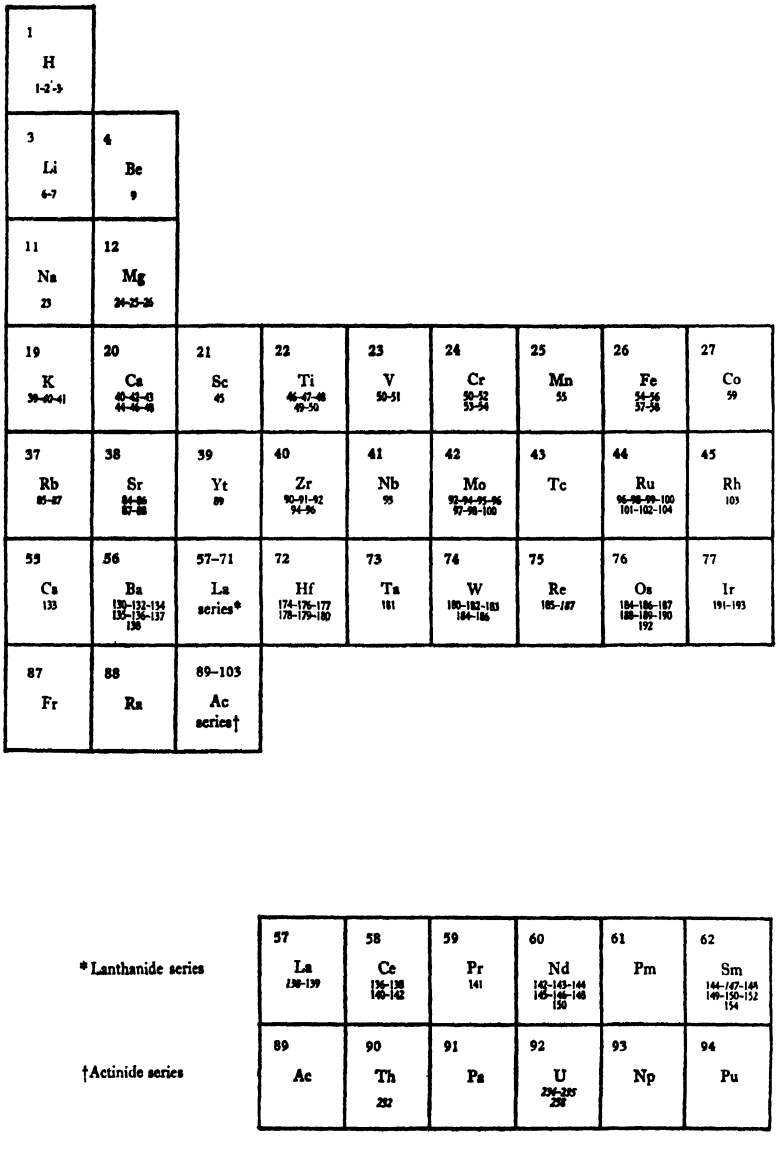


FIG. 1. PERIODIC CLASSIFICATION OF THE ELEMENTS

The modern form of Mendeleev's Table. At top left of each square is the atomic number (Z). Under the symbol for each element are the mass numbers of its natural isotopes, those in italics being the natural radioactive isotopes of long half-life. All the elements located in the same vertical column are chemically

							1 H 1-2-3	2 He 3-4
			5 B 10-11	6 C 12-13-14	7 N 14-15	8 O 16-17-18	9 F 19	10 Ne 20-21-22
			13 Al 27	14 Si 28-29-30	15 P 31	16 S 32-33-34	17 Cl 35-37	18 Ar 36-38-40
28 Ni 58 60-61 62-64	29 Cu 63-65	30 Zn 64-66-67 68-70	31 Ga 69-71	32 Ge 70-72-73 74-76	33 As 75	34 Se 74-76-77 78-80-82	35 Br 79-81	36 Kr 78-80-82 83-84-86
46 Pd 102-104-105 106-108-110	47 Ag 107-109	48 Cd 106-108-110-111 112-113-114-116	49 In 113-115	50 Sn 112-114-115-116 117-118-119 120-122-124	51 Sb 121-123	52 Te 120-122-123 124-125-126 128-130	53 I 127	54 Xe 124-126-128 129-130-131 132-134-136
78 Pt 190-192-194 195-196-198	79 Au 197	80 Hg 196-198-199 200-201-202 204	81 Tl 203-205	82 Pb 204-206 207-208	83 Bi 209	84 Po	85 At	86 Rn

63 Eu 151-153	64 Gd 152-154-155 156-157-158 160.	65 Tb 159	66 Dy 158-160-161 162-163-164	67 Ho 165	68 Er 162-164-166 167-168-170	69 Tm 169	70 Yb 168-170-171 172-173-174 176	71 Lu 175-176
95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

similar (for instance, H, Li, Na, K, Rb, Cs, Fr). The elements in the last column (He, Ne, Ar, Kr, Xe, Rn) are chemically inert because their outermost electron shells are saturated. The lanthanides, or rare earths (57 to 71), form a separate series with element number 57, and the actinides, elements 89 to 103, similarly form a separate series. There are shown separately. All the actinides are radioactive.

(water—two atoms of hydrogen linked with one of oxygen). Other molecules, in organic chemistry, can be extraordinarily complicated. For instance, the insulin molecule is composed of several hundreds of atoms of hydrogen, carbon, nitrogen, oxygen, and sulphur. Its molecular weight—sum of the atomic weights of its atoms—is 5733.

All material things, such as water, sugar, and wood, are made up of mixtures of prodigious numbers of molecules. All living things are composed of very complex molecules. Yet this immense diversity and complexity comes from a combination of a mere handful of different simple substances.

And these simple substances, or chemical elements, listed above, can be placed in categories. For example, sodium and potassium are very alike. If we classify all the elements according to their similarities, we make what is called a periodic classification, and form a table known as Mendeleev's Table (Fig. 1).

Elements that appear in the same vertical column in the table are chemically similar. Elements 57 to 71 form the special series called the 'rare earths.' They are very difficult to separate from each other because they are almost completely similar, chemically speaking, to one another and to lanthanum. This is why they are called the lanthanides. They are listed separately at the bottom of the table.

Elements 89 to 103, called the actinides, are also grouped together and with actinium. All are radioactive. We will come back in detail to the radioactive elements in the following chapter.

In the last column of the table are the rare gases, from helium to radon. These inert elements do not react chemically, and are of marginal interest to the chemist, since molecules including them cannot be synthesized under present experimental conditions.

The great success of Mendeleev's classification stemmed from the fact that when it was published in 1869 a certain number of squares were empty, since elements corresponding to the assigned properties were not known. However, these elements were discovered in actual fact, and fairly soon, all having the exact properties forecast.

Atomic Structure

This concept can be very well explained by examining specifically the structure of an atom. What is an atom? It is the ultimate

stage reached in the subdivision of a simple substance. If we were to put some helium gas in a flask, the gas would fill the receptacle, but we would be able to take half the quantity present, then again half of that and so on. We would have progressively smaller amounts of gas. But this dividing process is not infinite. A time would come when the mind could conceive of a limit. This limit would be the atom of helium.

We know that in 11 litres of helium gas there are 606,000,000,000,000,000,000,000 atoms of helium. A sphere of 28 centimetres diameter contains this number (called Avogadro's number) of atoms, whose smallness is thus made tangible. Each atom measures a hundred-millionth of a centimetre.

Our imaginary halving operation thus appears in a new light. Suppose our recipient contained 11 litres of this helium—we know that at normal conditions of temperature (15°C) and atmospheric pressure (760 millimetres of mercury) it would contain these $6{\cdot}06 \times 10^{23}$ (6·06 times 10 multiplied by itself 23 times; another way of writing the long number above) atoms. If we attached a vacuum pump to it, the number of atoms would become smaller and smaller as the pump sucked out the helium and expelled it. If the pressure dropped to one-millionth of a millimetre of mercury there would still be 270,000,000 atoms per cubic centimetre! It is believed that in interstellar space there must still be one atom per cubic centimetre. Thus, it is only in these regions of the universe that our visualization becomes a reality and that the dilution of matter is such that the individual atom becomes significant.

To find atoms we must go down to the infinitesimally small, and the foregoing paragraphs on helium can be applied to an atom of iron, an atom of silver, or an atom of lead. What distinguishes them one from another is their intrinsic composition. All have the common property of containing a central attracting nucleus with a set of electrically charged particles, the electrons, which travel at incredible speeds far from this nucleus (see Chapter 2).

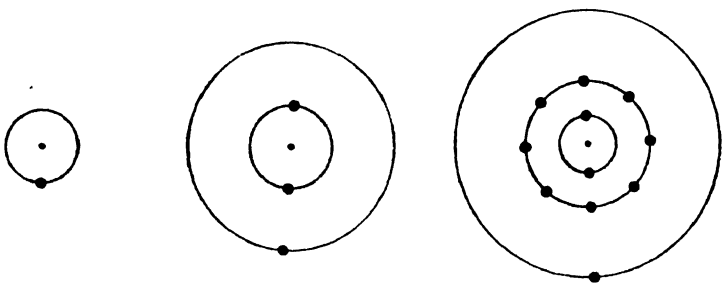
The most important law which must be noted in this theory of the structure of different atoms is that the atom of hydrogen has a single electron, the helium atom has two, the iron atom has 26, and the uranium atom 92. Thus, the underlying reason for the periodic classification begins to appear. The assignment of an

atomic number to each element is not arbitrary, but represents a fundamental law which gives what one might call a 'personal description.' The total number of electrons distinguishes each atom, and is the number assigned to the element in the periodic table.

Electron Shells

Mendeleev's Table becomes perfectly clear when it is realized that the shells of the electrons obey precise arithmetical laws. They lie in successive paths. The first is complete when it contains two electrons. The second and the third can contain up to eight electrons. The fourth is complete with 18 electrons, as is the fifth. But the chemical behaviour of the atom is determined by the electrons of the outermost shells, and it is by exchanging electrons on these shells that atoms associate in chemical combinations. Furthermore, internal electron shells are saturated, and there will be different atoms having the same number of electrons on their outer shells. Hence the chemical analogy between similar elements of the periodic table.

For example, H, Li, and Na can be represented schematically as follows:



Atom of hydrogen: 1 external electron

Atom of lithium: 3 electrons—2 internal and 1 external

Atom of sodium: 11 electrons— 2 internal, 8 intermediate, and 1 external

Fig. 2. Three Atoms of Chemically Similar Elements (1 external electron)

These three atoms share the peculiarity of one single electron in their outermost shell. This means their chemical behaviour is the same.

The inertness of the rare gases (which are listed in the last column of Mendeleev's Table) becomes perfectly clear: their external shells contain all possible electrons already—two for helium, eight for neon and argon, 18 for krypton and xenon, and 32 for radon. The structure thus achieved is very rigid and electrons in such shells cannot exchange with electrons from other atoms in the formation of molecules.

To end these few remarks on atomic theory, it is expedient to point out that the electron arrangement affects the physical properties of matter.

Electricity is a current of free electrons which are liberated from the central attraction of the nucleus.

These electrons travel through the inter-atomic spaces in considerable numbers at a speed of a few centimetres per second[17] in metal filaments such as electric cables or the tungsten filaments of electric lamps.

All the foregoing demonstrates how atomic theory has broadened in the last 50 years. The atomic concept of matter reveals not only the basic nature of material things, but also gives a very simple explanation of physical and chemical phenomena which are inextricably complicated when their source, albeit a single one, is not known. It is because matter is made up of 90 different elements that the world is as we know it. This breathtaking achievement of the human mind is the finest example of what true science can discover and accomplish.

17. And not at the speed of light, 186,282 miles per second in a vacuum, as is often stated.

2

Isotopes and Radioactivity

PEOPLE use the terms 'atomic physics' and 'nuclear physics' interchangeably, as if they were identical and synonymous. This is not so. Atomic physics deals with the whole of this very complex structure, the atom—that is, the central nucleus and all the planetary electrons. Nuclear physics originates in the study of the nucleus alone, and takes the mind into a world whose smallness defies the imagination, since the nucleus is only an imperceptible dot, ten thousand times smaller than the atom, and infinitesimal in human dimensions.

Let us take a look at two worlds at the extreme ends of the list of naturally occurring elements: the hydrogen atom and the uranium atom.

If we represent the nucleus of the hydrogen atom (a single proton) as a walnut with a diameter of one inch, its single electron will be found 570 yards from the centre. In these conditions, the uranium nucleus is like an orange with a diameter of four inches, surrounded by 92 electrons in layers ranging from 180 yards to 1800 yards from the centre.

These comparisons show how little matter there really is inside an atom. A further one will make the idea more tangible still. If the hydrogen nucleus were a ball with a diameter equal to the height of the Eiffel Tower, then its electron would be more than 7500 miles away, and the diameter of the whole atom would be 15,000 miles—or nearly twice that of the earth.

Now we come to this mysterious nucleus which hides the potent energy man is beginning to use without quite knowing what it really is.

Nuclei are as complex as atoms. Atoms, as we have seen, are not impenetrable spheres, but small swarms of particles gyrating in almost complete emptiness. The nucleus is an agglomeration

of particles called nucleons. But there are two varieties of nucleon: the proton and the neutron. The proton is electrically charged, the neutron is not. It would seem that the neutron is a proton plus 'something' which neutralizes its charge. This is shown by the fact that when a neutron becomes free in space, it eventually changes into a proton and an electron. The electrical charges on the electron (negative) and the proton (positive) are equal. The electrically neutral atom, therefore, has as many protons in its nucleus as there are electrons around it. For example, the calcium nucleus contains 20 protons; it is also element number 20, characterized by 20 planetary electrons. Similarly, the uranium atom will have 92 protons and the rest in keeping.

Neutrons do not affect the chemical properties of the atom. There are generally at least as many as there are protons, but the number can vary. For instance, calcium, with its 20 protons, can have 19 neutrons, or 20, or 21, or 22, or up to 29 neutrons. To be complete in our description of an element we must therefore take account of the number of neutrons. Atoms that are chemically identical but contain different numbers of neutrons, and so have different weights, are called isotopes.

The etymology of this word is evident—from the Greek *isos topos*, the same place—that is, the same square in Mendeleev's Table. The various calcium nuclei mentioned should be placed in the twentieth square since all contain 20 protons. But they will be distinguished by the total number of nucleons (neutrons plus protons) that they contain. This number is the mass number and it indicates the relative differences in mass, or weight, between the atoms.

We will thus have: calcium-39 ($20p+19n$); Ca-40 ($20p+20n$); Ca-41 ($20p+21n$) . . . Ca-49 ($20p+29n$). Not all these isotopic varieties of calcium exist in nature. Isotopes 40, 42, 43, 44, 46, and 48 exist normally, the others are radioactive and have relatively very short half-lives. It is only because the nuclear physicists have created them artificially that we know them.

Before dealing with radioactivity, let us take a last look at the normal state of things—that is to say, at matter as it exists around us. We said that there are only 90 simple substances. But we now see that each element can appear in various nuclear states. Matter is a mixture of the various isotopes of the elements.

Calcium, which we have taken as a concrete example, is a well-known element found in chalk and human bone and is a mixture of:

Ca-40	96·97	per cent.
Ca-42	0·64	per cent.
Ca-43	0·145	per cent.
Ca-44	2·06	per cent.
Ca-46	0·0033	per cent.
Ca-48	0·185	per cent.

These six nuclei are stable, they coexist in nature, and a mixture of them in the indicated percentages gives element number 20, calcium as we know it.

Another look at Mendeleev's Table (Fig. 1, p. 28) will show that at the bottom of each square is the mass number of all the stable isotopes, existing in nature, of each element.

Among other things, the table shows that silicon, element number 14, is a mixture of three isotopes:

Si-28	92·27	per cent.
Si-29	4·68	per cent.
Si-30	3·05	per cent.

But aluminium, element number 13, has only one stable isotope, Al-27. In general, elements with an odd atomic number have only one or two stable isotopes, while elements with even numbers have several. Tin, element number 50, has the largest number of stable isotopes.

In all, 275 stable isotopes exist in nature, plus nine which, although radioactive, have very long half-lives.

Beta Activity

This is the second time we have met radioactivity. In the preceding section we spoke of the calcium isotopes 39, 41, 45, 47, and 49, and then of the nine natural, but unstable, isotopes.

Radioactivity is the emission by a nucleus of a particle or of electromagnetic waves. The emission of the former modifies the nucleus and ends in a transmutation. The nuclei of the 275 stable isotopes emit nothing.

Carbon-14 is an unstable isotope, found in nature in small quantities because cosmic radiation from outer space is continually producing it at high altitude. This nucleus emits a beta

particle, which transforms one of its neutrons into a proton. Thus, starting from a nucleus with six protons and eight neutrons, the beta activity in question transforms the C-14 into a nucleus with seven protons and seven neutrons, that is to say into an N-14 nucleus, one of the two natural isotopes of nitrogen.

The inverse transformation also exists. A proton can become a neutron, and the nucleus involved will emit a beta particle, no longer negative, but positive. For instance, carbon-10 is transmuted into boron-10 (natural).

The nuclear physicist is faced with tables such as that in Fig. 3, overleaf. Each column contains the different isotopes of a given element, from number 4, beryllium, up to nitrogen, number 7. The isotopes are indicated by their mass numbers in the vertical column. The radioactive isotopes are indicated by rectangles, and the direction of disintegration by arrows which point to the stable end-product. The table clearly shows the transformations: carbon-10 ending in boron-10, carbon-14 in nitrogen-14. But these radioisotopes (radioactive isotopes which disintegrate) are short-lived, and are created artificially by appropriate nuclear reactions (in particular in cyclotrons), and a given quantity of a radioisotope is transmuted within a characteristic period of time.

This period is called a half-life, and is by definition the time in which half a given quantity of a radioisotope disintegrates. Radioactive decay and the intensity of radiation from a sample are directly connected. If, for example, we had at our disposal 128 grammes of carbon-11 (a perfectly gratuitous supposition since this isotope can be produced only in trace quantities), after 20 minutes only half the amount of carbon-11 would still be in existence—that is, some 64 grammes—and the other 64 would have become boron-11. In the next 20 minutes, half the remaining 64 grammes would have changed, and we would have 32 grammes of carbon-11, and 96 of boron. After the next half-life, there would be 16 grammes of carbon, and successively eight, four, and two after six half-lives.

Each radioisotope has a half-life. That of carbon-14 is considerably longer at 5600 years. Beryllium-10 is again much more long-lived, since it takes 2,500,000 years to lose half its activity. On the other hand, boron-12 is particularly ephemeral with a half-life of 0·027 second.

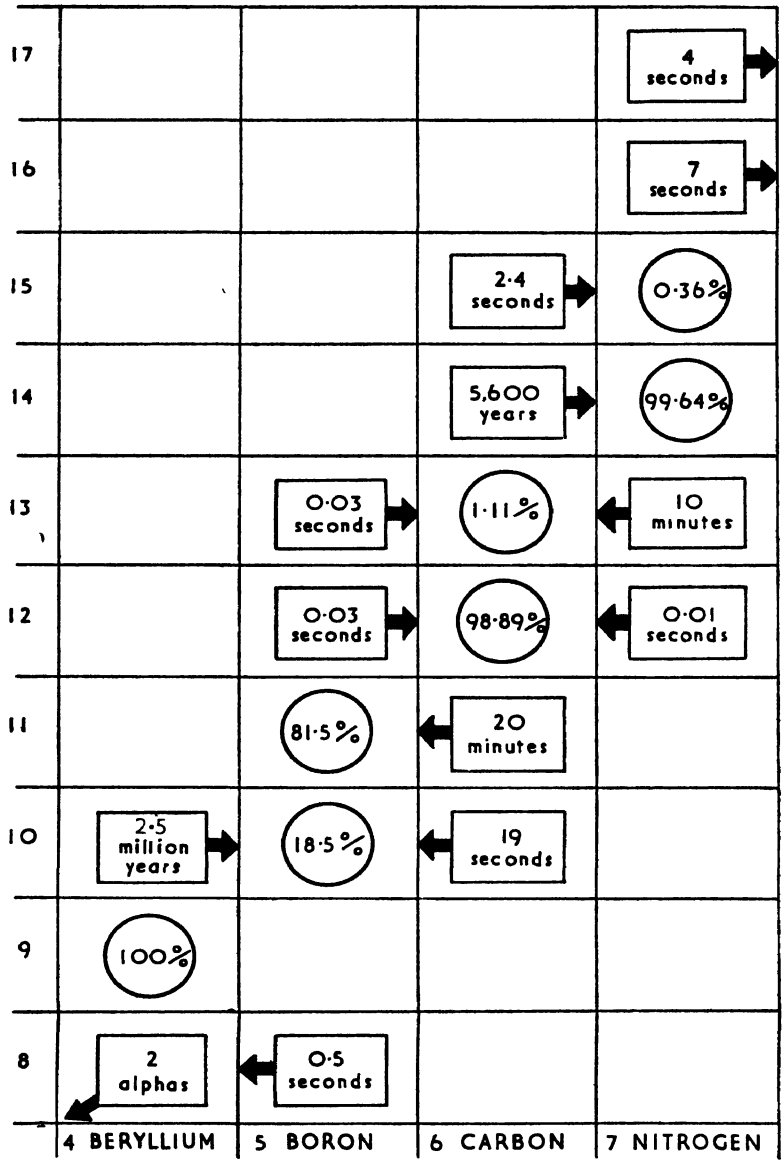
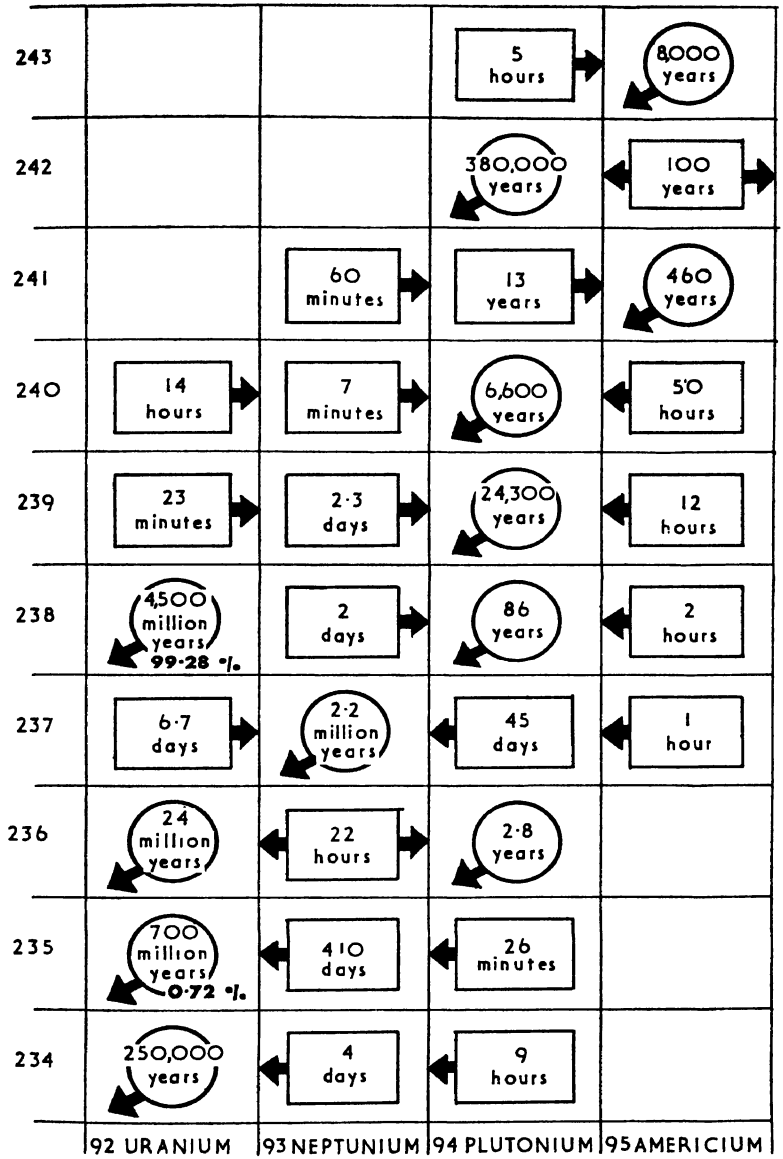


Fig. 3. Two Examples of Isotope Distribution

Table of the isotopes of four light elements: beryllium, boron, carbon, and nitrogen. Vertically, the mass number, *A* (sum of the protons and the neutrons in the nucleus). In the circles are the stable isotopes with the relative proportions found in nature. In the squares are the radioactive isotopes with their half-lives. The arrow indicates the direction of disintegration and the stable isotope in which the chain ends.

Note. Be-8 is an exception because it disintegrates into two alpha particles.



This table of a few isotopes of four heavy elements—uranium and the three transuranic elements that follow—completes the ideas developed in the table of light elements. It enables the reader to relate isotopes, mentioned throughout this book, to one another. U-235 and U-238 are the two heaviest natural isotopes. All the others have been synthesized since 1940, especially plutonium-239 (by the ton, in nuclear reactors). The arrows from the rectangles indicate a beta disintegration (minus to the right, plus to the left). The circles indicate isotopes analogous with the stable isotopes of the light elements, but here all emit alpha particles. The oblique arrows symbolize this alpha activity (for example, Pu-239 ends directly in U-235). The time given inside the circle is the half-life.

At the other end of the table of elements we have uranium-238 with a half-life of 4,500,000,000 years. This enormous value explains why, although it is radioactive, this element still exists in the earth's crust. The age of the earth is of the order of 4,000,000,000 years, so that about half the uranium atoms initially present are still in existence. The same applies to a greater or lesser degree to eight other naturally occurring radioisotopes whose mass numbers are indicated in italics in Mendeleev's Table. They are:

Potassium–40	1,400,000,000 years
Rubidium–87	60,000,000,000 years
Lanthanum–138	200,000,000,000 years
Samarium–147	150,000,000,000 years
Lutetium–176	75,000,000,000 years
Rhenium–187	4,000,000,000,000 years
Thorium–232	14,000,000,000 years
Uranium–235	713,000,000 years

Alpha and Gamma Activity

Thorium-232, uranium-235, and uranium-238 give birth, through their radioactivity, called alpha activity, to isotopes—also radioactive—of elements 91, 89, 88, 87, 86, 85, and 84. But their half-lives are relatively short—that of radium-226 being 1600 years. These isotopes of the elements between bismuth and uranium exist on earth, but solely because they are in radioactive equilibrium with their progenitors—Th-232, U-235, and U-238.

These three isotopes disintegrate with the emission of a particle designated alpha, which is simply a nucleus of element number 2—helium. It is a particularly coherent and stable grouping of two neutrons and two protons.

There is a third form of radioactivity called gamma activity, fundamentally different from the two others, alpha and beta. It is the emission of an electromagnetic wave which has analogies with light and with X-rays, but of much shorter wavelength and, in consequence, of considerable energy.

This type of radioactivity does not modify the nature of the isotope emitting it—the isotope simply loses some of its energy.

The following table summarizes the three types of radioactivity:

	Nature of the emission	*Speed of the particle in miles per second*	*Penetration in:* *Air*	*Body*	*The emitting nucleus being Z,A[1] the resulting nucleus is:*
ALPHA	Alpha particle = helium nucleus (2 protons + 2 neutrons)	6214 to 18,600	A few cm	0·1 mm	$Z-2$ $A-4$
BETA	− Negative electron	155,300	A few tens of cm	A few mm	$Z+1$ A
	+ Positive electron	155,300	A few tens of cm	A few mm	$Z-1$ A
GAMMA	Photon (Electromagnetic wave)	186,282 Speed of light	Several hundred metres	Passes through	Z A

The foregoing brief notions of radioactivity present no difficulties and should be known by any educated person. They pave the way to a full understanding of nuclear energy, and especially of the exact nature of the danger to life inherent in the use of radioactivity because of the certain rise in environmental radiation.

1. Z is the atomic number, number of the element in the classification and number of protons in its nucleus; A is the mass number, number of protons plus number of neutrons.

3

Fission, Fusion, Reactors, and Nuclear Bombs

THE release of nuclear energy results from two kinds of nuclear event, one called fission, and the other fusion (in the sense of a massing together). This release can take place in a fraction of a second, and will then be a bomb-like explosion. With fission, on the other hand, it can be controlled, and take place very slowly in a nuclear reactor.

FISSION, BOMBS, AND REACTORS

The origin of this energy lies in the nuclei of atoms, which we know are tightly linked structures of protons and neutrons. The nuclei of the heavy elements, such as uranium, contain more than 200 nucleons (92 protons and 143 neutrons for uranium-235), which are bound together by forces specific to the nucleus. The breaking of these links requires in most cases a supply of energy, but can take place, in certain other cases, with a release of energy.

This is what happens for certain heavy nuclei. The nucleus of uranium-235, that of uranium-233, and that of plutonium-239 have the peculiarity of being able to absorb a free neutron of low energy. The nucleus thus formed vibrates in such a way that it breaks and separates into two groups of nucleons; in other words, it 'fissions.' The two new nuclei obtained are those of much lighter elements (see Chapter 4) and this splitting of the atom frees energy, imparted to the fragments as well as to several liberated neutrons.

These free neutrons are sufficient in number (generally two to three per fission in the case of uranium-235) to cause, in turn, the fission of neighbouring nuclei. This reaction spreads from one to another with multiplication of the neutrons present and the release of considerable energy (200 MeV per fission on an average).

This simple mechanism immediately suggests two possible ways of releasing energy.

1. An unhampered reaction in which neutrons proliferate at a rate of a new generation each hundred-millionth of a second in a compact mass of fissionable isotopes. After 80 generations the fissions will be in such numbers that a mass of about one kilogramme will be involved, and gigantic energy will be released in an infinitesimal period of time. But to do this the mass of fissionable element must be sufficiently large for neutrons to be unable to escape before having struck and fissioned a nucleus. A minimum mass is thus necessary. At and above this value the reaction we have described will take place. Below this value, known as the 'critical' mass, the fission reactions take place but without spreading effectively through the mass. Above it, on the other hand, the yield of the reaction increases enormously. It can be raised to a marked degree by placing a neutron reflector all round the fissionable mass. More of this at a later stage.

2. If the number of neutrons in successive generations is controlled by absorbing all neutrons which are in excess and might speed up the reaction too much, it will be possible to master the fission process and allow it to proceed at a selected rate. We will then have a 'nuclear reactor' in which fission takes place according to a tightly-controlled programme, and in which energy is released by heating of the pile.

There is a marked difference between the two processes, although they both involve the same nuclear events. In the case of explosions the neutrons are of high energy and fission is caused by an intense flux of unmoderated (not slowed down) neutrons. In the case of reactors, usually very slow neutrons cause fission. These are called thermal neutrons because they are in thermal equilibrium with their surroundings. At room temperature their mean energy is 0·025 electron-volt (eV) and their most probable velocity 7260 feet per second, which is quite slow compared with fast neutrons.

Neutrons must therefore be slowed down and made to lose the energy they possess at the moment of the fission from which they issue. In these conditions a reactor must contain a moderator, usually graphite or heavy water, whose role is to compel fission neutrons to lose their energy through a succession of collisions with the nuclei of carbon or deuterium (heavy water

contains two—sometimes one—atoms of heavy hydrogen, or deuterium, to one of oxygen).

Fusion

The synthesis of nuclei from lighter nuclei is far more fundamental than fission, because it is by these reactions that the sun and the stars pour into space a flux of energy of astounding prodigality.

Electrical repulsion prevents the nuclei (positively charged by their protons) from coming into contact, except when they have enough kinetic energy to surmount this barrier. A very high temperature must be reached for the nuclei to gain enough speed to penetrate each other, forming new and more complex nuclei. This, the 'thermonuclear' process, is still the subject of experiment on Earth, but it goes on continually in the stars. The heart of the sun is at a temperature of some 13,000,000 °C and terrific pressure, and this allows the free protons (hydrogen nuclei) to fuse and form—after the loss of a positive charge—a deuteron (proton plus neutron). Similarly, two deuterons can fuse to form a nucleus of element number 2, helium.

There are a number of possible combinations, such as:

1 proton +1 proton =1 deuteron + 1 beta-plus particle
1 proton +1 neutron =1 deuteron
1 proton +2 neutrons=1 tritium (extra-heavy hydrogen) nucleus
2 protons +1 neutron =1 helium-3 nucleus
2 protons +2 neutrons=1 alpha particle (helium-4 nucleus)
3 protons +3 neutrons=1 lithium-6 nucleus
3 protons +4 neutrons=1 lithium-7 nucleus

And there are possibilities of reactions between the products on the right of the equations and primary particles.

These various reactions, possible at very high temperatures (50,000,000 °C at least), are the sources of the thermonuclear energy which provides the explosive power of the H-bomb.

Controlled fusion is still in the experimental stage, and scientists are striving to produce it by passing high intensity electrical discharges through tubes containing deuterium. This seeks to cause collisions and fusion of deuterons by raising their temperature. The technical difficulties are considerable and will be discussed in Chapter 5.

Three corners of the nuclear energy square are known, the fourth not yet (Fig. 4).

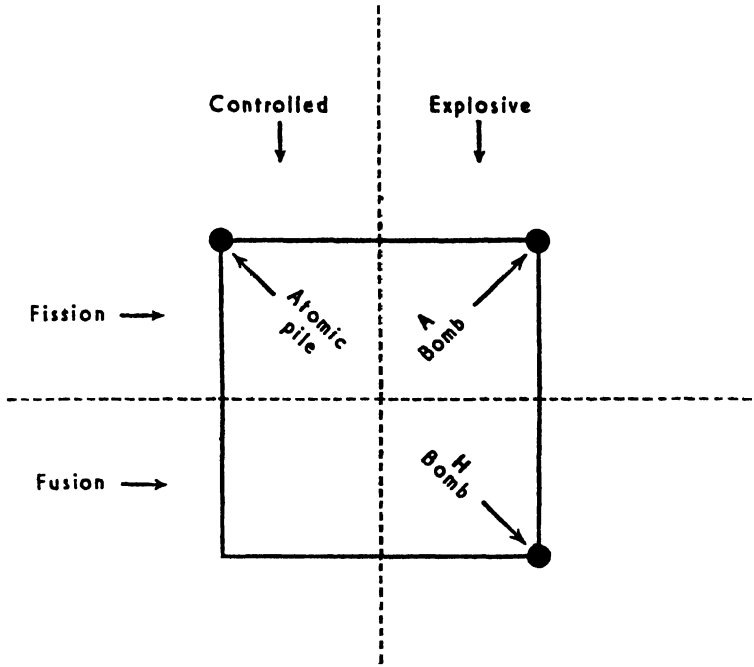


FIG. 4. THE NUCLEAR ENERGY SQUARE

CONTROLLED REACTIONS AND NUCLEAR REACTORS

It is disconcerting to read descriptions of nuclear reactors that say they are quite small—at least as far as the essential part is concerned—and yet at other times speak of gigantic structures the size of a block of flats. This is because of the different moderators and 'fuels' that can be used.

The core of a reactor using enriched uranium as fuel and heavy water as moderator is small: a cylinder of one to two yards in diameter will contain it. If the fuel is natural uranium and the moderator graphite, the core will be large: a cube of about 10 yards.

The question of enrichment is very important. Natural uranium is a mixture of two isotopes: uranium-235 to the extent

of 0·72 per cent., and uranium-238 to the extent of 99·28 per cent. There are also traces of U-234.

However, it is the 235 isotope which undergoes fission when struck by a slow neutron; U-238 splits only under bombardment by high energy (at least 3 MeV) neutrons. Then, if a uranium rod cased in its magnesium sheath is placed in one of the channels in the graphite of a large reactor, the thermal neutrons with which it is literally impregnated will strike the uranium nuclei. To simplify the discussion, because the series of reactions are extremely complex, suppose that seven nuclei of U-235 are struck for every 993 of U-238. The seven become nuclei of U-236 which fission and can release zero, one, two, three, or four neutrons (generally two or three). The neutrons which strike the U-238 nuclei are either deflected or, in some cases, captured. The U-239 isotope thus formed transmutes to form neptunium-239, which is again transmuted into plutonium-239 with a half-life of 24,300 years. A reactor is thus not only a source of (thermal) energy through the fission of U-235, but also a source of plutonium-239, which is another fissionable substance, through capture of neutrons by U-238 nuclei.

The uranium bars can be 'enriched' in U-235—that is, their content of this isotope can be increased compared with the natural percentage of 0·72. This is done in special plants, by a gaseous diffusion method, in Britain, the U.S.A., and Russia. It is thus possible to produce uranium metal enriched to 1 per cent., 2 per cent., 10 per cent., 20 per cent., up to 93·5 per cent., the technical limit of the process. Uranium enriched only up to 2 per cent. or 3 per cent. is already an excellent fuel, and its fission properties permit a sharp reduction in the size of the reactor cores. It is very expensive, however.[1]

The essential components of a graphite moderated natural uranium reactor are the core, which is a mass of about 100 tons of uranium in bar form, canned in magnesium, and placed in a

1. Britain and France have been the protagonists of the graphite moderated natural uranium reactor, and the United States has favoured relatively high enrichment. Britain is now building an advanced reactor, which will use very slightly enriched fuel to enhance performance, while the U.S.A., with an eye on the fact that enrichment costs in other countries are three to four times higher than her own, appears to be dropping reactor types which need too rich a fuel, and even to be studying certain natural uranium types.

geometrical pattern, or lattice, in a structure of graphite blocks weighing some 1000 tons. The whole is surrounded by a thick shield of between 30,000 and 40,000 tons of concrete which absorbs the major part of the intense radiation from the core. Pipework is provided to feed in and carry away the coolant (air, water, gas, according to the type of reactor) which passes around the bars of fuel and removes the fission heat. Rods made of cadmium or of boron steel, which can be inserted and retracted through the core by servo-motors, provide for the absorption of excess neutrons, and can automatically maintain reactor output at a constant level, or shut down the reactions in case of a dangerous power increase or of a runaway.

Heavy water moderated reactors, much more compact, consist of a tank filled with the heavy water in which the canned fuel bars are submerged. The tank is surrounded by a graphite neutron reflector, and the heat is removed by the moderator itself. Biological protection is again given by a thick concrete shield.

The power of the first type of reactor (graphite, natural uranium) has thus far been pushed up to nearly 1,000,000 kilowatts (thermal), yielding about 300,000 kilowatts of electrical energy. Furthermore, plutonium is produced at a rate of about one gramme per 1000 kilowatts (thermal) per day. This plutonium has to be extracted by chemical processing from the uranium bars discharged from the reactor at intervals varying between four and fifteen months. The processing also removes fission products, while the purified uranium, although depleted in uranium-235, can still be used.

A 100,000-kilowatt (thermal) reactor produces some 100 grammes of plutonium per day or around 35 kilogrammes per year—enough to make six or seven atom bombs.

Of course there are many varieties of reactor. The whole of the atomic policy of the United States since 1950 has been to construct a large number of experimental medium-power reactors and a few large stations in order to find out by experience the best characteristics and the optimum operating conditions. It would be too technical to go into details at this point, and it is best merely to list the main types.

1. *Pressurized Water.* The pressurized water reactor (PWR), used by the United States Navy in its submarines, uses water

under heavy pressure—it does not boil—passing directly through the core to moderate and remove nuclear heat.

2. *Boiling Water.* The boiling water reactor (BWR) can be made much less complex than the preceding type by using a direct cycle from the reactor to the turbines instead of primary and secondary circuits. Steam and turbine contamination from faulty fuel elements is a major consideration.

3. *Sodium-cooled.* This reactor uses a liquid metal (sodium) to remove the heat. Advantages are better thermal properties and low pressure circuits; disadvantages are neutron absorption by, and activity of, the coolant metal, which is also highly inflammable. All three types use enriched uranium fuel.

4. *Homogeneous.* Experiments are in progress with homogeneous reactors where the reacting mass is a solution of a highly enriched uranium salt (uranyl sulphate, for instance) in heavy water contained in a spherical vessel. This can be surrounded by a 'blanket' of heavy water to reflect neutrons, or by a blanket of natural uranyl sulphate solution in heavy water to reflect neutrons, but also to capture some neutrons and breed fresh fissionable material. A major disadvantage is the intense corrosiveness of the solution.

5. *Organic Moderated.* This type uses high boiling point hydrocarbons (terphenyl) as moderator and coolant. It gives promise of reactors running at low pressures and constructed from ordinary steels, but it needs enrichment.

6. *Breeder Reactor.* This type does away with moderators and operates on highly enriched fuel, giving an intense flux of fast neutrons. Spare neutrons are absorbed in a surrounding blanket of natural uranium to form plutonium-239. The cores are small and the heat density in them high; and liquid metals must be used to remove the heat.

It should be possible to build a nuclear power-plant with a fast breeder reactor that would produce electricity and, at the same time, more plutonium in the breeder blanket than the fissionable material being transmuted in the core.

7. *Gas-cooled Reactor.* Many more reactors of this last type are under construction or planned than of the foregoing types. France and Britain favour this type and together have built 11 reactors and are building a further 16—all of the gas-cooled, graphite-moderated, natural uranium fuel variety. The type is

flexible, and experiments are in progress to adapt it for high temperature operation with slightly enriched fuel and refractory metal canning, and for very high temperature operation with highly enriched fuel, graphite canning, and some breeding in the thorium mixed in with the fissionable material of the fuel.

There are also research reactors as well as reactors for the production of radioisotopes for industrial, medical, and scientific applications, but these do not come within the scope of this book.

Explosive Reactions and Nuclear Bombs

In the case of a nuclear explosion, the fissions take place in a very short period of time in the heart of a mass of fissionable material. A new generation of neutrons is born every hundred-millionth of a second, and in 80 generations there will be about one gramme of neutrons which will effect the fission of about one kilogramme of U-235, U-233, or Pu-239, the three fissionable isotopes. The time taken by the detonation is thus barely one-millionth of a second, and it is in this very brief period that most of the energy is released—23,000,000 kilowatt-hours or 20 kilotons.

But this prodigious energy release takes place in a volume about that of an orange and, from the start, there is a tendency for the reacting mass to be dispersed. If this is permitted, the reaction will stop. To improve the energy yield, dispersion must be prevented as long as possible. The critical mass must be held together, and if only a hundred-millionth of a second is gained, the energy released is doubled since a supplementary generation of neutrons is obtained. All the progress made in a few years in the destructive potential of atomic bombs has resulted from this search for maximum cohesion of the critical mass.

The two possible ways of producing an explosion are well known.

The first consists in making a number of perfectly machined sections of small quantities of fissionable material and, at the instant of the explosion, pushing them together with considerable force so that they fit together into a spherical or cylindrical mass surrounded by a neutron reflector. The final mass must, of course, be more than the critical mass. A chemical explosive is used to throw the sections together and, for a brief instant, oppose dispersion.

The other way of producing a detonation is by an implosion, which takes advantage of the fact that critical mass is affected by density. The critical mass for uranium containing 93·5 per cent. uranium-235 is [1][2] 38 kilogrammes for a density of 9, 25 kilogrammes for a density of 13, and only 17 kilogrammes for a density of 18·8.

Suppose, for instance, that the charge of nuclear explosive of a bomb consists of a sphere of 17 kilogrammes of uranium powder of density 10. At the moment of detonation, shaped charges of conventional explosive placed around the uranium are made to explode simultaneously. This compresses the central sphere very strongly, and increases its density to over 19. Since both critical density and critical mass are exceeded, the explosion takes place and the yield must be considerable, since when the system of shaped charges detonates, it produces an inward thrust opposed to dispersion forces—the desired effect.

Critical Masses

Values of critical masses have been the subject of a great mass of literature for some fifteen years, as they were considered for some time to be the 'secret' of the bomb. These values were made public in 1957 [1] for a mixture called oralloy. This term was first used in 1949 to describe uranium enriched up to 93·5 per cent. in uranium-235 and containing 6·5 per cent. of uranium-238. Its density is 18·8 and the value of the critical mass is sharply affected by a number of factors: shape,[3] and especially the nature and thickness of the neutron reflector which surrounds it. It is hard to realize how important this question of reflected neutrons can be: small accidental releases of fission energy were set off in U.S. laboratories because, among other things, a researcher had put his hand close to a quantity of fissionable material well below the critical mass. The water contained in his hand acted as a reflector, and for a moment increased the flux of neutrons that were escaping from and being reflected towards the fissionable material.

2. Numbers given in bold type in square brackets refer to the bibliography.

3. The cylinder, much easier to construct, is at least as efficient as the sphere. The critical mass passes through a minimum when the height is equal to 0·8 of the diameter.

The best reflector is beryllium metal (element number 4), followed by beryllium oxide, tungsten carbide, natural uranium, and tungsten metal. In this respect uranium is specially effective because the explosion is caused by fast neutrons which also fission some of the uranium-238 atoms of the reflector, thereby adding fractionally to the energy released.

The critical mass for oralloy is 55 kilogrammes unreflected; 18·5 kilogrammes with a uranium reflector 10 centimetres thick; 23·5 kilogrammes if the latter is only 5 centimetres thick; and 30·8 kilogrammes if the reflector thickness is cut to 2·5 centimetres. With a beryllium reflector 10 centimetres thick, the critical mass drops to only 14·1 kilogrammes. The report adds that these critical masses are valid for U-233 and Pu-239 if divided by three. The density of plutonium is 15·6, and that of uranium-233 is 18·5, so that the extreme values for the critical masses of these two isotopes would appear to be 16 kilogrammes without reflector; 6 kilogrammes with a thick uranium reflector; and 5 kilogrammes with a beryllium reflector.

Finally, just as the charges of uranium-235 are not completely pure—contrary to widely held beliefs—since they still contain at least 7 to 8 per cent. of U-238, plutonium-239 charges are impure since in the production reactors this isotope undergoes a capture reaction competing with fission reactions, and is transformed into the Pu-240 isotope which is extracted with the 239 during fuel processing. As long as the Pu-240 is less than 10 per cent. of the explosive charge, the critical mass is only slightly increased, since this isotope also fissions, but not so easily as Pu-239.

Thermonuclear and Compound Explosions

Little official data has been released on the technical aspects of these gigantic explosions. It is therefore, important to avoid too much guesswork, because nuclear science is extremely complex and in reality far richer than the simplifications of the popular Press and the explanations of 'science for all.'

Thermonuclear bombs are certainly very complex devices in which several phenomena take place simultaneously, and which display several phases.

Two facts are now certain: they contain lithium and tritium, and have uranium and/or thorium in an external (or internal)

shell, while the neutron flux they produce is fantastic—representing several kilogrammes of momentarily free neutrons against one gramme for the 20-kiloton fission bomb. Their lithium content has been proved by the detection of this element high in the atmosphere [89, 90]. Tritium has been found in rain and surface water all over the world, although it is not known whether this isotope is a remnant of nuclear explosive, or a result of the reactions. We will deal with lithium and tritium in Chapter 17.

Natural uranium and thorium are used in large amounts because the fission products dispersed after each H-bomb explosion are so abundant that they must come from the fission of several hundred kilogrammes of these elements. On the other hand, the isotopes U-237 and Th-231 have been detected by the Japanese in fall-out of U.S. and of Soviet origins, and these are formed by the $(n, 2n)$ reaction which consists in the expulsion of two neutrons from the new nuclei formed when U-238 and Th-232 have each absorbed one neutron.

The fact that the neutron flux is extremely high has been published to account for the formation of very heavy isotopes of elements 98, 99, and 100 through these experimental superexplosions. The abundant production of carbon-14 from atmospheric nitrogen also bears witness to the intensity of this flux.

We will come back to these questions later in this work in the section on the dangers of atomic energy which deals with the worldwide consequences, both present and long-term, of these experimental explosions—the negative aspect of this new energy which has fallen into the hands of a human race insufficiently evolved to make use of it in the way it deserves.

4

Fission Products

THIS chapter is not indispensable for the general comprehension of our subject, but it must nevertheless be written and read, because it forms an introduction to the discussion that follows. It is not possible to understand the problem of storing radioactive wastes, or the problems of radioactive fall-out, if the nature of fission products is unknown, since these fission products are both the radioactive wastes and the radioactive fall-out. This chapter is, therefore, a little more technical than the others, but it will be essential for anyone who wishes to understand the underlying import of the major problem of nuclear energy based on fission.

Fission, as we have seen in the preceding chapter, is the breaking of a heavy nucleus, of one of the elements situated at the end of Mendeleev's Table. For example, a neutron is absorbed by a U-235 nucleus. The new nucleus, U-236, vibrates in such a way that it is deformed and breaks into two much lighter nuclei, which lose a few excess neutrons. These two nuclei belong to elements which come in the middle of the Table.

FISSION PRODUCT NUCLEI

To go into more detail, U-236 nuclei contain 92 protons and 144 neutrons. Of the latter, none, one, two, or three (mean number: 2·4) can be expelled. Let us suppose that two are expelled, then the two new nuclei must contain together 92 protons and 142 neutrons.

We could then have a nucleus with $Z=37$ protons and 57 neutrons; the other would necessarily have $Z=92-37=55$ protons, and $142-57=85$ neutrons. The first would be a nucleus of rubidium-94 (rubidium is element number 37), and the second a nucleus of caesium-140 (caesium is element number 55).

The fission of uranium-236 thus results in the formation of two nuclei which we have identified. But we arbitrarily chose the first, the second being being imposed by arithmetic. We could have said the first nucleus would have $Z=38$ protons and 52 neutrons, and in this case the second would have had 54 protons and 90 neutrons. The first would have been strontium-90, and the second xenon-144. These possible ways of splitting the nucleus are only two among many. In a mass of uranium-236 undergoing fission, the fission products consist of a mixture of a fairly large number of radioactive isotopes belonging to elements from number 32—germanium—to number 66—dysprosium—that is, to 35 different elements among the 92 in the classification.

But it would appear that if $Z=32$, the second nucleus formed can have only $Z=92-32=60$ and not 66; or that if $Z=66$, then the second nucleus must have $Z=92-66=26$ and not 32. The two extremes indicated do not appear to be compatible. This is due to the fact that the new nuclei formed are radioactive, and that all fission products are electron emitters (beta negative radioactivity). The two nuclei formed immediately after fission are unstable; they emit electrons, and at each emission the Z number increases by one. Initially, the lives of these transmuting isotopes are very short, but lengthen as they come closer to transformation into stable isotopes. Germanium-72 and dysprosium-162 are the two stable extremes observed among the fission products of uranium, but the isotopes which end up with these mass numbers started off with atomic numbers which agreed with the law of conservation of mass, their half-lives being too short for observation.

In intermediate cases the chain of daughter-products is easy to establish. Several fairly long ones are known, such as:

Kr-93	Rb-93	Sr-93	Y-93	Zr-93	Nb-93*	Nb-93
2 sec	short	7 min	10 hrs	1,000,000 years	6 years	stable

* Excited nucleus.

This is the chain relating to mass number (A) 93. It starts with one of the krypton isotopes and ends with niobium-93, which is stable, after passing through six transmutations. The initial daughter-products have short half-lives, but that of zirconium-93 towards the end of the chain is immense, at 1,000,000 years.

Thus, in fission products, radioactive wastes, and fall-out from nuclear explosions, there exists an isotope of which half will still be active 1,000,000 years from now. It is Zr-93, and this is not the only one (see the table at the end of this chapter).

Graphs of Fission Product Yields

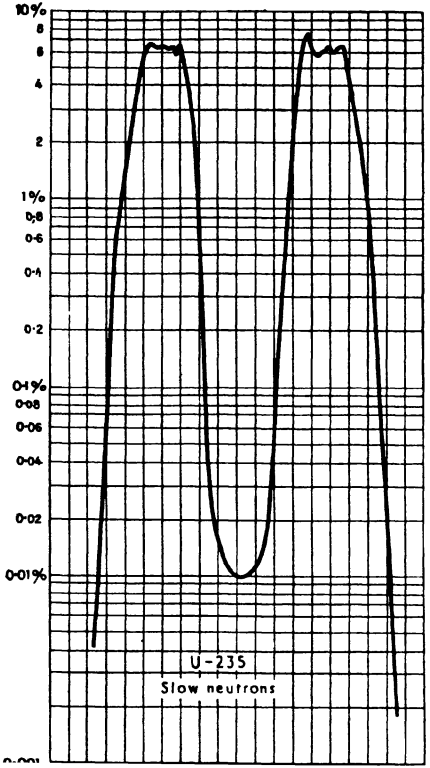
Fission products are classified not according to the atomic numbers of the elements to which they belong but by the values of their mass numbers (A), ranging from 72 to 162. The yields of the various products are not equal. More nuclei are formed with mass numbers around 95 than around 115—as many as 600 times more. It is not known why heavy nuclei struck by a neutron break asymmetrically (one light, one heavy nucleus), instead of symmetrically (two nuclei of equal masses). This explains the shape of the curves in the graphs overleaf. (Figs. 5 and 6) [2].

Fig. 5*a* is well known, being the graph of the percentage of nuclei formed according to mass numbers in the case of a uranium-235 nucleus absorbing a slow neutron—as in nuclear reactors. We find that 6·5 per cent. of the fission nuclei will have a mass number of 100, or that 0·9 per cent. will have $A=105$; 3 per cent. will belong to the group where $A=131$ and 7 per cent. to the chain where $A=134$.

This production curve for fission products is the ABC of nuclear energy. When we say, for example, in the Conclusions (p. 219) that 300 kilogrammes of caesium-137 have been spread around the world as a result of nuclear tests, it is because this production curve has told us that the chain $A=137$ is produced in 6 per cent. of cases. The same applies to strontium-90. It is one of the unfortunate coincidences of nuclear physics that $A=90$ and $A=137$ are among the most abundant of the fission products, that is to say strontium-90 and caesium-137, which are precisely the most dangerous for living organisms. Strontium is an element similar to calcium, and caesium is similar to potassium (see Fig. 1, Mendeleev's Table, p. 28). But calcium and potassium are two vital constituents of living organisms.

The curve in Fig. 5*a* holds in its shape all the drama brought into human existence by nuclear fission.

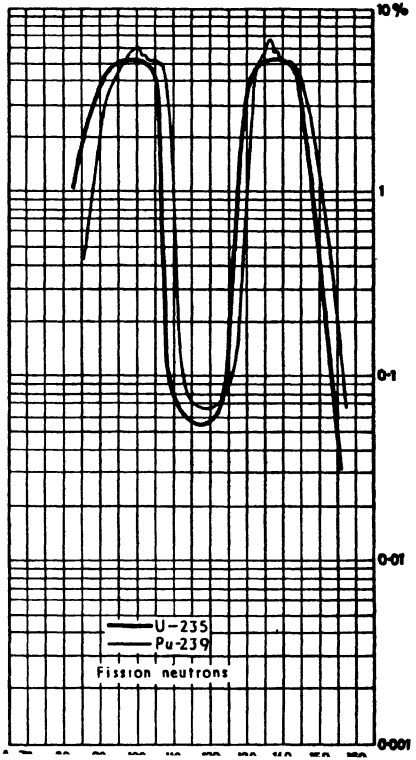
Figs. 5*b*, and 6*a*, 6*b*, and 6*c*, underline certain important facts. The relative yields of fission products differ according to the



FIGS. 5*a* AND 5*b*. DISTRIBUTION OF FISSION PRODUCTS IN FUNCTION OF THE MASS NUMBER (*A*), THE FISSIONABLE ISOTOPE, AND THE ENERGY OF THE INCIDENT NEUTRON

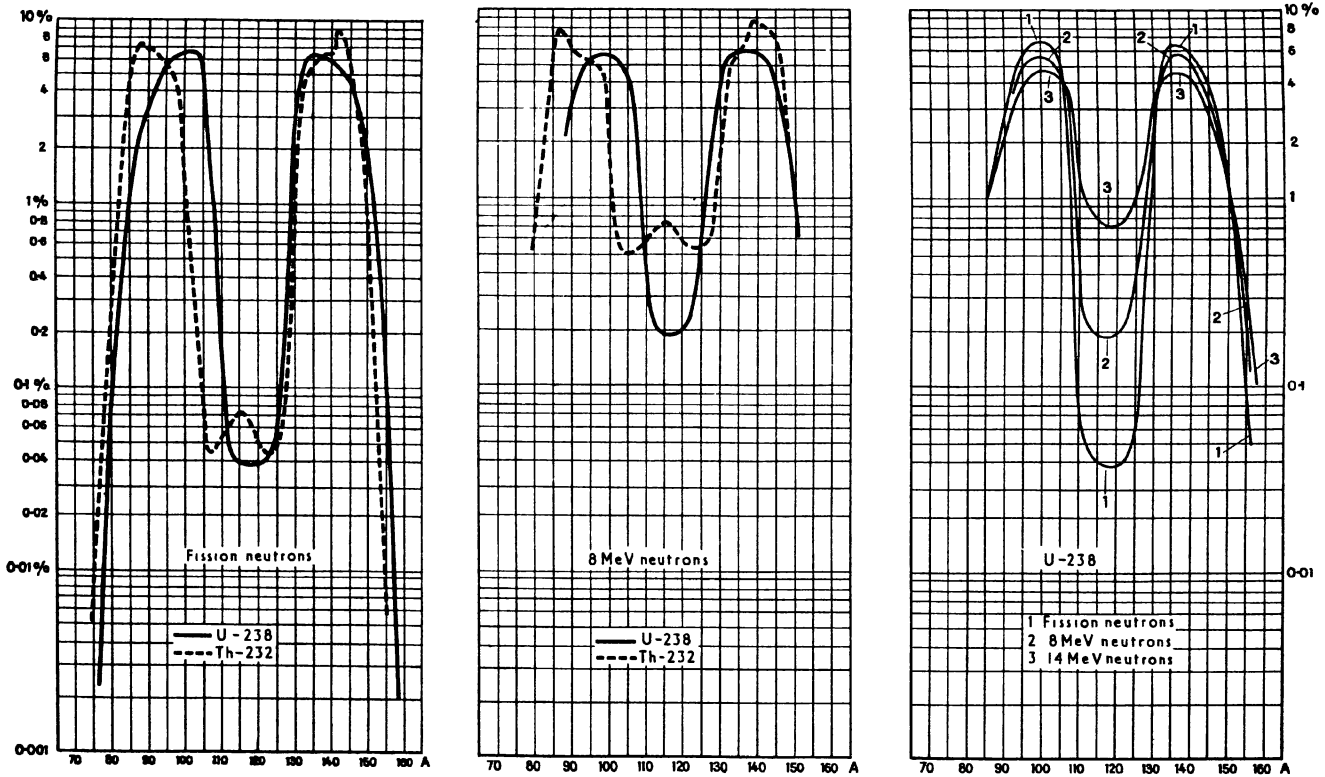
Left. Curve relating to the fission of uranium-235 by slow neutrons, as in an atomic pile.

Right. Curves relating to the fission of uranium-235 and plutonium-239 by fast fission neutrons as in atomic bombs. Note the difference between the two curves and the considerably higher position of the central minimum. Isotopes of mass numbers from 115 to 125 are six times more abundant in nuclear explosions than in reactor wastes.



FIGS. 6*a*, *b*, *c below*. GRAPHS COMPARING FISSION PRODUCT YIELDS FROM THE FISSION OF THE URANIUM-238 AND THORIUM-232 SHELLS OF THE H-BOMBS EXPLODED AT BIKINI IN 1954

The composition of the fall-out varies somewhat according to the energy of the incident neutrons in view of the fact that the nuclear processes involved change at various energy levels. (See p. 58.)


10 %
8
6
4
2
1 %
0·8
0·6
0·4
0·2
0·1 %
0·08
0·06
0·04
0·02
0·01 %
0·001
70 80 90 100 110 120 130 140 150 160 A
Fission neutrons
U - 238
Th-232
8 MeV neutrons
U-238
Th-232
U-238
1 Fission neutrons
2 8 MeV neutrons
3 14 MeV neutrons

fissionable isotopes from which they come and the energy of the neutrons present. This is an important fact to which the scant literature on the subject pays no attention. Fig. 5*b* gives the fission product distribution for U-235 and Pu-239 fissioned by fast neutrons. This is what happens in atom bombs. If we compare it with Fig. 5*a*, we see immediately how fallacious it would be to take the composition of radioactive wastes from a nuclear reactor as a criterion for the study of nuclear fall-out. Fission products from a uranium-235 nucleus split by a fast neutron are six times more abundant at the minimum in the distribution curve than those from the same nucleus split by a slow neutron. In the case of plutonium, there is a displacement in the curve which greatly modifies the distribution of mass numbers. For $A=110$ there is 1 per cent. in the case of Pu-239 against only 0·08 per cent. in the case of U-235.

These differences are greatly accentuated in the case of heavy nuclei fissioned by high energy neutrons. And we have seen that the major part of the energy of the thermonuclear bombs is derived from high energy neutrons. What then will be their effects on the uranium-238 or thorium-232 of the H-bomb shells? Figs. 6*a* and 6*b* give the fission product yields from these two isotopes, the first with fission neutrons, and the second with 8 MeV neutrons of which there must be a large proportion in any thermonuclear process. It is obvious that the composition of the radioactive fall-out from composite thermonuclear explosions is very different from that which results from A-bombs. In particular, production of strontium-90 is several times greater in the case of thorium than in the case of uranium, while the amounts of isotopes of mass numbers between 110 and 115 are several times larger.

Fig. 6*c* reproduces the two preceding graphs for U-238 only, and adds the graph for neutrons of 14 MeV to show clearly the effect of increasing neutron energies. However, neutrons of all these energies are present among the incredible numbers released in an H-bomb explosion.

Fission Product Isotopes with Long Half-Lives

The following table will complete this data [4, 7]. It is a list of fission product isotopes with a half-life higher than five days. They are classified in ascending mass numbers so that they can

be referred to quickly when encountered in the text. The data given are: the symbol of the element, the mass number A, the half-life, the percentage of total fission product yield in the case of U-235 fissioned by thermal neutrons (reactor) according to reference [4], the energy of the beta particles, and, if there are several, their percentages and the gamma rays if any. The asterisk indicates an excited state of the nucleus.

Isotope	*Half-life*	*Per-centage*	*Beta (MeV)*	*Gamma (MeV)*
Se-79	60,000 yrs	0·05	0·16	
Kr-85	10·6 yrs	0·3	0·68	0·5
Rb-87	5×10^9 yrs	2·5	0·27	
Sr-89	51 days	4·8	1·5	
Sr-90	28 yrs	5·8	0·55	
Y-91	58 days	5·4	1·5; 0·3 (0·2%)	1·19 (0·2%)
Zr-93	10^6 yrs	6·5	0·05	
Zr-95	63 days	6·2	0·38; 0·89 (2%)	0·7; 0·23 (2%)
Sr-96	6/10 days	6·3	?	?
Tc-99	200,000 yrs	6·1	0·3	
Ru-103	40 days	3	0·2 (90%); 0·1; 0·7	6 from 0·05 to 0·6
Ru-106	1 yr	0·4	0·04	
Pd-107	7×10^6 yrs	0·2	0·04	
Ag-111	7·5 days	0·02	1·1; 0·7 (8%)	0·24; 0·34 (8%)
Cd-113*	5 yrs	?	0·6	0·26
Cd-115*	43 days	0·0007	1·6; 0·7 (2%)	4 from 0·3 to 1·4
Sn-117*	14 days	0·001		0·15
Sn-119*	275 days	?		0·06; 0·02
Sn-121	5 yrs	?	0·42	
Sn-123	131 days	0·0013	1·4	
Sn-125	9·5 days	0·013	2·37; 0·4 (5%)	8 from 0·2 to 2
Sb-125	2 yrs	0·02	0·6 (18%); 0·3 (49%) 0·13	11 from 0·1 to 0·64
Te-125*	58 days	0·005		0·11
Te-127*	105 days	0·035		0·09
Te-129*	33 days	0·35		0·1
I-129	17×10^6 yrs	0·9	0·15	0·04
I-131	8 days	3·1	0·6 (88%); 0·3; 0·2	6 from 0·08 to 0·7
Xe-131*	12 days	0·024		0·16
Xe-133	5·2 days	6·6	0·34	0·08
Cs-135	3×10^6 yrs	6·4	0·2	
Cs-137	30 yrs	6·15	0·5; 1·17 (8%)	0·66
Ba-140	13 days	6·4	1 (75%); 0·4	6 from 0·03 to 0·54
Ce-141	32 days	6	0·58; 0·4 (75%)	0·14
Pr-143	14 days	5·7	0·93	
Ce-144	290 days	6	0·3 (76%); 0·17	0·08; 0·13
Nd-147	11 days	2·7	0·8 (66%); 0·4 (18%) 0·2	9 from 0·1 to 0·7
Pm-147	2·6 yrs	2·7	0·2	
Sm-151	90 yrs	0·45	0·08	0·02
Eu-155	1·7 yrs	0·03	0·15 (80%); 0·24	8 from 0·02 to 0·15
Eu-156	15 days	0·014	2·4	0·09
Tb-161	7 days	8×10^{-5}	0·5 (70%); 0·45 (22%) 0·4	5 from 0·02 to 0·13

Note: The disintegration chains corresponding to mass numbers 124, 148, 152, and 154 are not known, probably because of the existence of an unidentified long half-life isotope.

This table has been simplified. The decay chains are more complex in certain cases since all the isotopes given do not necessarily end up in a stable isotope; there are other disintegrations. This is the case for strontium, important because of its biological effect. Once ingested, the strontium-90 nucleus emits its beta particle of 0·55 MeV (maximum) and gives birth to a nucleus of yttrium-90, also radioactive and with a half-life of 64 hours. It emits a negative beta of 2·26 MeV and a gamma of 1·7 MeV, the resulting product being stable zirconium-90. In consequence, to appreciate the organic effects of ingested fission products, all the isotopes into which the ones indicated above decay must be known, and the totals of beta and gamma radiation must be added up.

To give the complete tables of disintegration chains and go further into this subject would be outside the scope of this work.

PART II: THE FRIEND

5

Energy

ANY discussion on nuclear energy is helped if an idea can be formed of how much energy is derived from conventional sources throughout the world.

We know that energy drives all things from the earthworm to the cyclone. All the energy which living things need comes, in the final analysis, from the sun's radiation. It is this electromagnetic radiation (light and infra-red) which is transformed into chemical energy by the action of vegetable chlorophyll. The organic molecules synthesized by plants are used by herbivorous animals, while carnivores find an easy source of calories by digesting molecules that have previously been built up by other animals.

But instead of vital energy, we are here concerned with mechanical, driving, and heating energy, which the world needs in constantly increasing amounts. Technically advanced countries require each year 10 per cent. more energy than the year before —that is, they more than double their energy needs each decade.

What are the principal energy sources? The muscles of animals, waterfalls, vegetable fuels (wood), natural gas, hydrocarbons (petroleum, petrol, heavy oil), lignite, and peat and coal. The following table gives the total for each in thousand million kilowatt-hours and the percentage of the grand total for the world in 1952 [8]:

	kilowatt-hours (1,000,000,000)	*percentage of total*
Animal energy	300	1
Hydro-electric sources	400	1·4
Lignite and peat	1,300	4·5
Natural gas	2,700	9·3
Wood, etc.	4,600	15·9
Petroleum, petrol	7,700	26·5
Coal	12,000	41·4

This is valid for the production of energy. The figures for its effective utilization are much lower: barely one-third is used, in the following forms and proportions:

		kilowatt-hours (1,000,000,000)
Agriculture		300
Transport	Trains	110
	Boats	180
	Motor vehicles	380
Industry	Power	600
	Heat	5200
Domestic	Power	400
	Heat	2900

This represents a total of some 10,100,000,000,000 kilowatt-hours utilized against 29,000,000,000,000 produced, the remainder being wasted because of the inefficiency of all machines.

In comparison with these world figures, total U.K. electrical energy production in 1960 amounted to 129,500,000,000 kilowatt-hours. The French figure was 72,000,000,000, and the American was 840,000,000,000.

If we were one day to replace all other sources by a single one, that provided by the fission of uranium-235, present in natural uranium in a proportion of 0·7 per cent., we would have to fission 1300 tons of uranium-235, thus needing 200,000 tons of uranium ore each year. However, at present and for a number of years, production of uranium will not exceed 50,000 tons annually.

World Production of Uranium Ore

Uranium is an abundant constituent of the earth's crust. It is found almost everywhere, in a greatly diluted state in the sea, in phosphates, in metalliferous deposits, in granite, and, of course, in a whole group of minerals exploited in the uranium mines. In order to make exploitation worth while, uranium content must be several kilogrammes per ton of ore; other uranium-bearing materials contain between a few grammes and a few hundred grammes per ton and cannot be exploited at the present time.

The great uranium deposits are located in the Congo (approaching exhaustion), South Africa (where uranium is a by-product of other mining operations, such as the gold mines), Canada, the United States, Czechoslovakia, and Siberia.

World uranium prices have been tending continuously downwards, and from an early contract price of around 12 dollars per kilogramme of uranium oxide are expected to drop eventually to about 6 dollars per kilogramme. The United States Atomic Energy Commission's price for uranium metal is 40 dollars per kilogramme, while the first free international bid to supply natural uranium metal to the International Atomic Energy Agency for transfer to Japan fixed a price of about 35 dollars.

Production of uranium oxide (U_3O_8) in countries in the Western Hemisphere in 1959 is put at some 42,000 tons, of which Canada supplied 15,909 tons, the United States 16,390, South Africa 6200, the Belgian Congo 2000, and Australia 1000 tons. Estimates for the Eastern Hemisphere vary between 10,000 and 20,000 tons, the Soviet Union and Eastern Europe accounting for about 6500 tons of the total. Western production for 1960 was probably around 45,000 tons, far above actual consumption, which is put at about 17,000 tons per year. Most of the latter figure is accounted for by military requirements—plutonium-producing reactors and uranium sent to the isotope separation plants for the production of enriched material.

Civil demand for uranium remains small since the nuclear power-plants are at the prototype stage. Only the United Kingdom has undertaken a large programme to construct nuclear power-stations. These will provide about 5,000,000 kilowatts by 1968, generating some 35,000,000,000 kilowatt-hours in that year. No other country has yet followed suit and, although each 1000 kilowatts of power need about one ton of uranium, current production of uranium is likely to exceed demand by a wide margin until 1970 at the earliest.

These estimates do not take account of the changes which are always possible in our ideas on the production of nuclear energy, since fission is not the only possible means. Fusion could one day upset all predictions and uranium would then serve no other purpose than to produce arms, its major use since 1944.

Domestic uranium production in France was about 100 tons

in 1948, 500 in 1957, and 800 in 1958, and is expected to reach a level of about 2000 tons with annual consumption in the 1960's of between 1500 and 1800 tons.

To return to world production of nuclear energy, current planning and building programmes are giving some countries nuclear electrical capacity. Britain expects to have some 3,000,000 kilowatts by 1965—the most ambitious programme—followed by the United States and the U.S.S.R., where the same figure may be reached a few years later. The leading nuclear energy users, the U.S.A., the U.S.S.R., the U.K., France, Euratom—could, by the end of 1970, have some 20,000,000 kilowatts of nuclear power, if all plans are carried out.

If this installed capacity is used to the maximum possible, which is about 80 per cent. of the time, or 7000 hours per year, it will give an output of some 140,000,000,000 kilowatt-hours annually. However, we have seen that total world energy consumption in 1952 was about 10,200,000,000,000 kilowatt-hours, and this figure will be at least doubled by 1970. Thus, the nuclear contribution would appear to be very small by comparison with the grand total.

Nevertheless, it must be noted that nuclear energy will produce electricity, whereas the world consumption figure was for all types of energy. Moreover, the energy figure applies only to those technically advanced areas where nuclear power reactors will be installed. Under these circumstances, the nuclear power production figures become much more significant and will represent an appreciable proportion of the electrical energy produced in these privileged countries.

It can be seen how the prospects of nuclear energy change according to the way in which the problem is approached. Some interested persons hailed nuclear energy as a miracle when its future possibilities began to appear; others believed that for a long time its contribution would be a drop in the ocean.

Some have seen in this birth of a 'new era' the end of the evils which afflict the world and a guarantee of future progress; others see in it a source of new evils which will only add to the existing heavy burden of human bondage. And, as always in such cases, the two extreme views each have their share of the truth.

We borrow from *Nuclear Power* of January 1961 the following data:

	Operating	*Building*	*Contracted for*
U.S.			
Power reactors in the U.S.	11	15	3
Power reactors for abroad	2	5	0
Military (Pu-producers) and Naval	26	32	10
Research reactors in the U.S.	89	3	1
Research reactors for abroad	19	7	3
	147	62	17
ABROAD			
National power reactors	25	24	3
Power reactors for export	0	4	0
National research reactors	57	4	0
Research reactors for export	6	4	0
	88	36	3

This table gives a very accurate picture of the state of nuclear development in the world. It shows that research reactors are more numerous in the U.S. than in any other country, since the former will have 93 once the current programme has been carried out while all other countries together will have 90. The same applies in the case of exported research reactors for which the U.S. figure will be 29 against only 10 for other countries which have a nuclear potential.

On the other hand, the United States is carrying out its nuclear power programme with great prudence compared with the research reactor programme. A total of 29 power-plants is given by the table, plus seven for export, against 52 in other countries, with four for export. The U.S. has an enormous energy potential in reserve, and does not need to lean on fission energy, while other countries, such as Britain, are pushing ahead with it as quickly as possible. It must, however, be noted that the first half of the table separates the power reactors from the big plutonium production reactors and from the reactors designed for marine propulsion. In the case of other countries, no distinction is made between the first two types. For example, in Britain, Calder Hall supplies electricity for general use, and the plutonium from the irradiated uranium fuel elements is extracted and can be used for bombs. In France, the three reactors at Marcoule give a small surplus of electricity, but are intended mainly to produce military plutonium. Only the Chinon nuclear station

is a true power-plant. The 52 stations of the second half of the table are, therefore, mostly for mixed purposes, and the figure does not truly represent an industrial potential.

The 68 U.S. military reactors should include the reactors built and to be built for the Navy. These figures are analysed in Chapter 6 which deals with nuclear propulsion. Meanwhile, by 1963, the U.S. expects to have 48 nuclear reactors for the propulsion of submarines and warships alone; the aircraft-carrier *Enterprise* will itself have eight reactors. The only non-military reactor of this type is that propelling the *Savannah*, an experimental commercial vessel.

Other interesting data this table yields is on world nuclear activities. At the beginning of 1961, 235 reactors were in operation throughout the world, 98 were being built, and 20 planned.

Of this total of 353, about 100 are, or will be, high energy reactors including 20 which produce, or will produce, between 50,000 kilowatts and 200,000 kilowatts each for their national grids.

The British Nuclear Power Programme

Instead of enumerating these 20 reactors country by country and going into descriptions of power-producing reactors whose characteristics are continually being changed by technical progress, and whose operational dates hardly ever coincide with forecasts, it is better to give a brief example of a national nuclear power programme, that now being brought into existence by Britain.

The map of Britain given in Fig. 7 opposite summarizes the whole programme and underlines its importance. There will probably be some ten double-reactor stations developing around 5,000,000 kilowatts by 1968, and later in the 1970's it may well be that no power-stations other than nuclear will be built. In addition, eight reactors are feeding a total of 300,000 kilowatts into the national grid at present, and as time goes by new designs of experimental and prototype power-producing reactors will come into operation.

The reason for this rapid build-up of a new source of energy is mainly because Britain's coal reserves are not inexhaustible. Consumption of fuel in terms of coal by the power-stations is put at 67,000,000 tons for 1965–66, including 53,000,000 tons of coal, 8,000,000 for other conventional fuel, the remainder

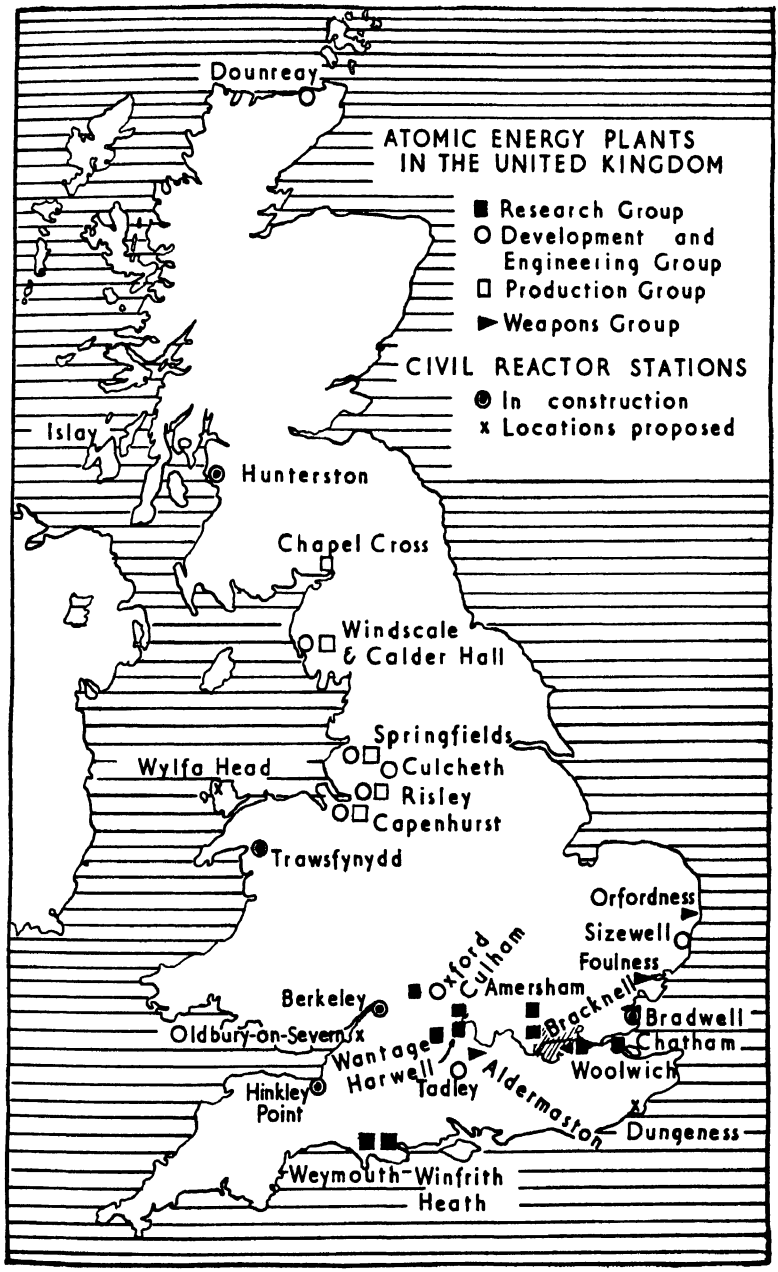

Dounreay
ATOMIC ENERGY PLANTS
IN THE UNITED KINGDOM
Research Group
Development and
Engineering Group
Production Group
Weapons Group
CIVIL REACTOR STATIONS
In construction
x Locations proposed
Islay
Hunterston
Chapel Cross
Windscale
& Calder Hall
Springfields
Wylfa Head
Culcheth
Risley
Capenhurst
Trawsfynydd
Orfordness
Sizewell
Foulness
Oxford
Culham
Amersham
Berkeley
Bracknell
Bradwell
Oldbury-on-Severn x
Wantage
Harwell
Tadley
Chatham
Woolwich
Hinkley
Point
Aldermaston
Dungeness
Weymouth
Winfrith
Heath

FIG. 7

coming from nuclear power. For 1970–71, the contribution from this new energy source will replace 17,500,000 tons of coal, but the Central Electricity Generating Board's stations will still be burning 66,000,000 tons of coal plus 5,500,000 equivalent tons of other fuels. By 1975 the C.E.G.B. figure will have risen to 115,000,000 tons in terms of coal, while the total domestic coal output figure for all types will have levelled out at about 200,000-000 tons some time before.

In 1959, early assumptions as to the cost of nuclear power were thrown out by unexpected trends. The costly power programme, on which work began in 1955, was based on estimates which postulated steady or rising prices for electricity from conventional sources. The cost of nuclear electricity, initially much higher than that obtained by burning coal, oil, or harnessing waterfalls, was expected to become competitive after a few years of experience and progress. But as coal and fuel oil prices dropped in the period during which the first A-stations were being built, while costs of conventional stations were also reduced, the cost of nuclear power, instead of catching up with the cost of power from conventional sources, remained somewhat higher. The break-even date is thought to lie between 1966 and 1970. Nevertheless, this has not been considered sufficiently serious to apply a brake to the development of nuclear power—at least, not in the United Kingdom, whose plans look to the distant future. According to the experts, these plans will bring a rich reward in time.

Britain is thus the only country to have gone all out for nuclear power based on fission, and the experience that she will have gained by carrying out all or—if it is cut down—part of her programme will serve the rest of the world, by now more circumspect towards the application of nuclear power. Britain is also carrying out a research programme comparable with those of the other great nuclear powers, seeking new reactor types, in particular with the fast breeder reactor at Dounreay in Scotland, based on a principle which we have already discussed (p. 48).

The U.S.A. and the U.S.S.R. also have nuclear power-stations in operation. The first in Russia was Kaluga (1954) and in the U.S.A. was Shippingport (1957).

The Swedish Programme

An interesting nuclear power programme is that being planned by Sweden, a country which is not among the atomic giants, but one which is at a very advanced stage technologically.

The official paper presented at the second Geneva Conference on the peaceful applications of nuclear energy [10] underlined the fact that Sweden has no deposits of fossil fuels and, on the other hand, that although hydro-electric installations are being actively developed, imports of energy range from two-thirds to three-quarters of total demand. After the Second World War, demand for electrical energy rose by 7 per cent., and overall energy demand by 4 per cent. annually.

Hydro-electric power covers normal demand with thermal power in reserve for peak periods and a margin to take account of rainfall. Hydro-electric potential of rivers and waterfalls that remains to be exploited will cover the increase in demand over the next 12 years or so. Imports of fuel, mainly petroleum, account currently for 20 per cent. of special import charges.

Sweden has worked out a plan which aims at reducing this dependence on imported petroleum and putting a brake on the increase in imports. The main object is to build reactors which will provide heating for whole regions, as well as electricity. The country has large deposits of shales containing about 300 grammes of uranium per ton, and the total uranium reserves are put at some 1,000,000 tons. A processing plant is being installed at Ranstad and is scheduled for operation in 1964–65. Meanwhile, a smaller plant at Kvarntorp is being modified to take imported ores of higher uranium content as well as semi-concentrates of uranium ore. Uranium metal output is expected to reach some 120 tons annually in 1964–65. Heavy-water production methods have been under intensive study.

In 1954 a 300-kilowatt research reactor (R1) using natural uranium and heavy water went into operation, and a Materials Testing Reactor of U.S. design (R2) became available for experimental work in 1959.

R3 is the code name for the first heating and power reactor which will supply a new suburb of Stockholm and is now expected to go into operation in 1963. It will be a pressurized heavy water reactor operated on natural uranium oxide, and will

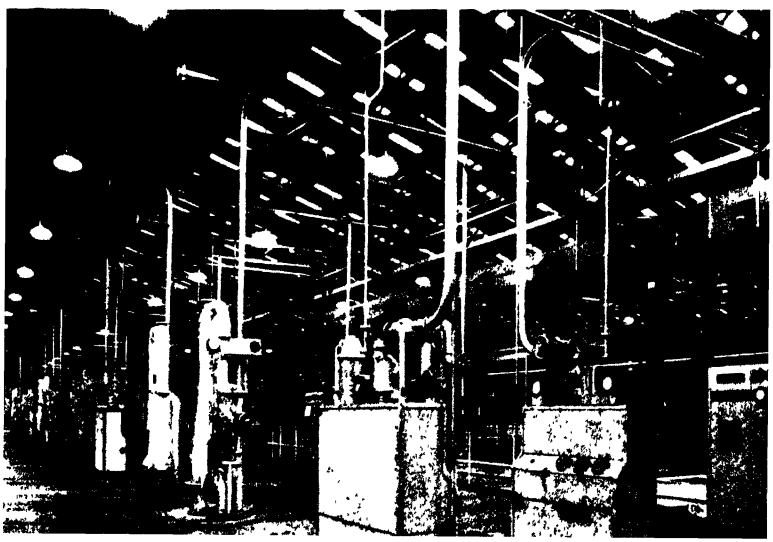
develop 15,000 kilowatts of electricity, and 75,000 kilowatts of heat. Work on R4, the Marvikens Power Station, is at the design and construction stage.

The two outstanding points in the Swedish plans are that the accent is on the heat released by present reactor designs, and the reactors are built in rock caverns. In the cold climates of the northern countries, the chemical combustion of wood and coal can be considered a wasteful heresy, and timber is a noble substance that is useful in so many ways that it is unacceptable to see it wasted by being burned to release calories which will not be efficiently used. On the other hand, fission energy is directly available in the form of heat, and it is natural to extract these calories and ensure inter-urban heating from a very compact source, while using a small fraction for electricity production. Moreover, it is quite logical to build these plants in caverns situated under mountains. The Swedes are great rock architects, and the siting corresponds to the idea which the general public has formed about the safety precautions needed for nuclear power-plants, both in peace and in war, since a reactor would be a perfect target for whoever sought to disorganize a whole province.

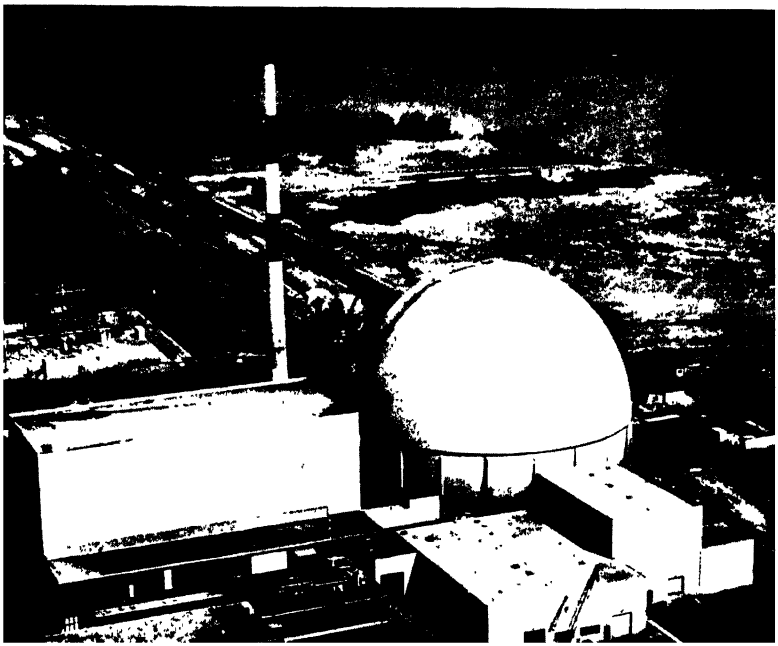
To sum up the section on the production of energy by nuclear fission, it can be said that the impetus given by the great nuclear powers is considerable.

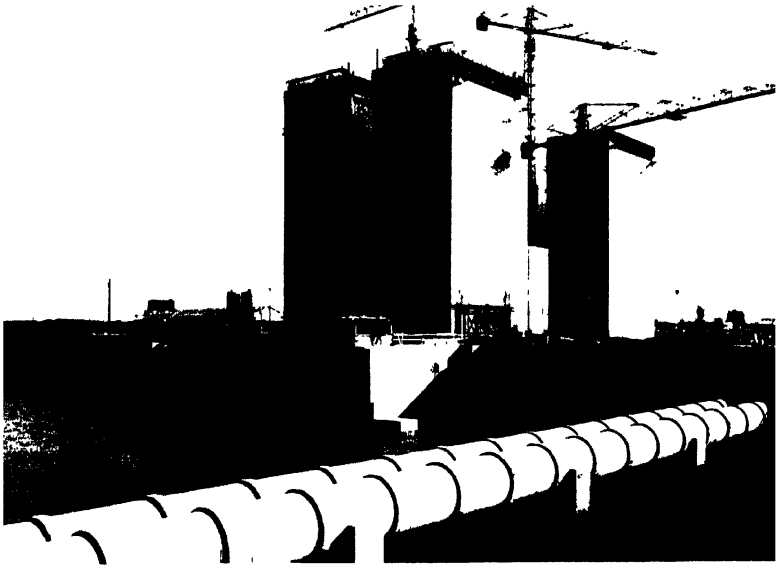
History gives few examples of such a generous technical contribution placed at the service of those developing a comparatively new discovery which is still far from having yielded the major part of its potential. However, it is clear that this astonishing mobilization of resources was brought about by the warlike uses of nuclear energy. If there had been no plutonium-producing reactors, nuclear power-stations would not be multiplying only 20 years after the discovery of fission. If there had not been an enormous production of enriched uranium in the isotope separation plants built for the production of U-235 (for bombs) we would not have seen so many possible applications. The uranium-235 and plutonium-239 of the atom bombs are the twin pillars on which the whole edifice of peaceful nuclear applications will be erected during the next decade. At the end of this period we will be better able to judge whether the bases were sound.

(Above) *Uranium mine in Queensland, Australia.* (Below) *This enormous diffusi plant, the largest in Europe, is at Capenhurst, in England. Here uranium isotopes c separated from each other, as they diffuse at different speeds.*

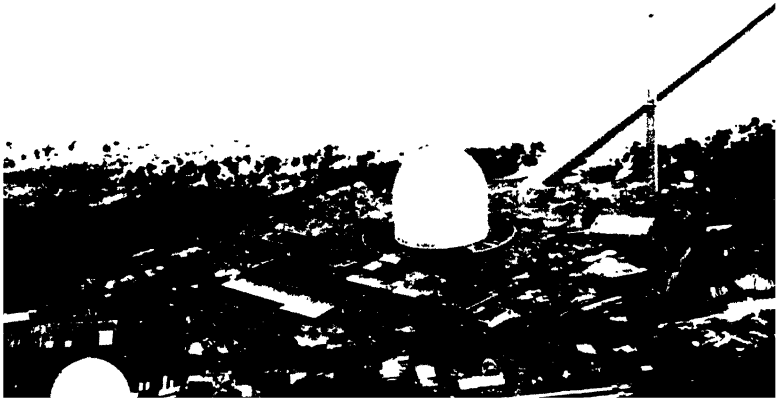


.bove) *Part of the large British nuclear power programme is this advanced gas-coolec* ictor at *Windscale. It will operate more economically than any previous gas-cooled,* aphite-moderated *reactor.* (Below) *The first American nuclear power plant to be* wolly *financed by private industry. It supplies the Chicago area, and it develops* 180,000 *kW of electricity.*





(Above) *Two French plants built at Chinon use gas-cooled, graphite-modera reactors. One is scheduled to develop about* 60,000 *kW of electricity, the ot* 140,000 *kW to* 170,000 *kW.* (Below) *This research reactor at Trombay, n Bombay, uses natural uranium fuel, is cooled by air and water, and is moderated heavy water.*



(Left) *A full-scale prototype o one of the miniature nuclea reactors being developed under th U.S. Atomic Energy Commis sion's SNAP programme. Suc a reactor is destined to provid auxiliary power inside spac vehicles.*

(Below) *A nuclear reactor de veloped to test the possibility o propelling space vehicles b nuclear power. The second suc project carried out for the U.S Atomic Energy Commission, thi is designated Kiwi-A-Prime.*

Miniature Reactors and Direct Conversion

Among all the astonishing possibilities of applying nuclear energy are some that are all the more outstanding because they shed new light on certain problems which have not yet been solved satisfactorily by conventional techniques. One example is that of obtaining a permanent supply of electricity from a very small source. SNAP 2—System for Nuclear Auxiliary Power—consists of a miniature nuclear reactor and generating system, whereas SNAP 3 uses a radioisotope to produce electricity. The SNAP programme is designed to produce units which will supply electrical energy for space vehicles, radio transmitters, telemetering equipment, and any instrumentation that requires an autonomous electrical supply produced by a source which is small, light, and permanent.

The miniature reactor SNAP 2 measures about 14 × 13 × 18 inches. It weighs some 230 pounds and drives a turbo-generator weighing 33 pounds. Total weight of the equipment is 660 pounds. The core is made of solid fuel elements of highly enriched uranium in a zirconium hydride moderator. It is cooled by liquid sodium-potassium alloy which gives up its heat to mercury in a heat exchanger. The mercury vaporizes at 358°C and drives a small turbine generating three kilowatts (or 1200 times more than SNAP 3—see overleaf). The cost of the development project resulting in SNAP 2 was 6,500,000 dollars, and later types of this device will cost 400,000 dollars each. SNAP 8, based on the above, will develop 30 kilowatts.

Direct Conversion of Nuclear Energy into Electricity

When fission is induced in the atomic nuclei of the fuel in a reactor it brings about a transformation of the binding energies within these nuclei. The fission product nuclei take part of this energy in the form of movement. This movement is braked and halted by the electrical action of the surrounding atoms. The kinetic energy is added to molecular agitation, and there is a temperature increase. The radioactive particles and radiation emitted upon or after fission are also absorbed, and further heating is produced. Nuclear processes thus end in heat production, and it is this heat which is used, not the primordial energy. This means that efficiency is very poor, amounting only

to a few per cent. In other words, the electric current produced by a nuclear power-station represents only a few hundredths of the energy released in the reactor core. At least 95 per cent. of this energy is lost on the way in the intervening steps: heat exchanges with one or two cooling systems; enormous heat losses in the condensers and especially because of the poor thermodynamic yield resulting from the fact that only a few hundred degrees separate the temperature of the coolant in the core and in the condenser.

Many improvements can be considered, all of which will considerably increase efficiency. But another possibility is under study, and this could radically modify the future development of nuclear power. It is the direct transformation of the kinetic energy of ionized particles into electric current. To do this, it would be necessary to 'canalize' the flux of positive ions and of negative electrons, thus producing an electric current. This device, simple enough to describe, cannot be built in the present state of the art. Instead, other intermediaries will have to be used, and these will absorb considerable amounts of energy of transformation, which always reduces efficiency. However, among all the possible intermediary mechanisms, some are very economical, especially those which avoid movement. To displace mechanical components inevitably brings about a considerable wastage of the primordial energy.

SNAP 3. Let us take a look at a most interesting device described officially by the White House on January 13, 1959. It is a small cylindrical apparatus, some 4·7 inches in diameter, 5·5 inches high, and weighing 5·5 pounds. SNAP 3 is a small electric battery which can develop up to five watts, and which is intended to provide current for the mechanisms carried in space vehicles.

This device had prototype costs of 15,000 dollars, and is expected to be copied at much lower prices. The source of its energy is element number 84, polonium—the first radioactive element discovered by Marie Curie. Polonium-210 has a half-life of 138 days and costs 10 dollars per curie. The prototype contained one-third of a gramme of the isotope—that is, about 1760 curies, which brought the cost of its fuel charge to 17,600 dollars.

The method of operation of the device is as follows. The radioactive charge has a half-life of 138 days, thus the electrical characteristics will vary with time. The full initial loading is

3000 curies, and is divided into two small pieces lodged at the centre of the device. Alpha particles of 5·3 MeV are emitted and absorbed by the polonium itself, and its temperature increases to 375°C while the power given off is 96 watts. A steel central capsule contains the polonium, and this is surrounded by a molybdenum cylinder to which are attached 54 coupled semi-conductors made of lead telluride. These ensure the generation of an electric current through the thermo-electric effect, the cold source being an external aluminium ring. Mechanical limitations make it impossible to cover more than 26 per cent. of the hot surface with the junctions of the semi-conductors. Nevertheless, the efficiency of SNAP 3 is 5·5 per cent. and this figure may be increased later. Power is 5·3 watts at full load and 2·5 watts after 138 days, while the voltage starts at 4·3 to drop to 3·5 at the end of one half-life.

The energy produced in one half-life—that is, over four months—is nine kilowatt-hours, which compares very favourably with 0·25 kilowatt-hours supplied by an ordinary dry battery weighing three kilogrammes or the 0·5 kilowatt-hours from the best silver/zinc batteries. The atomic battery is thus a source of power equivalent to that developed by current chemical means, but has considerably greater reserves of energy.

Polonium-210 can be replaced by cerium-144, which has a half-life of 290 days and gives double the capacity. Strontium-90, with a half-life of 28 years, could be used, but the energy yield would be considerably smaller, external heat losses would rise, and efficiency would be considerably lower. Nevertheless, the cost of a fuel charge would be much less, especially as some of the radioactive fission products could be extracted for this purpose from the troublesome radioactive wastes. Gamma emitters must be avoided, and in the case of polonium-210 the gamma activity is so low that the dose of radiation received at the surface of the apparatus amounts to only 0·7 röntgens per hour at full power, and to a dose 100 times less at one yard. Another possibility is to use plutonium-238: this isotope was employed in the Transit IVa satellite.

Controlled Thermonuclear Reactions

To conclude this chapter on energy, something must be said about the greatest promise of nuclear research, that of harnessing

'thermonuclear' energy—peaceful use of the fusion of the nuclei of light atoms.

To succeed in utilizing this energy, whose sources are inexhaustible compared with human existence, would be to re-create on Earth the immense heat and radiation fluxes of the stars. It is not yet known which process will enable us to start up and maintain a cycle of thermonuclear reactions. In the stars these reactions can be produced only in zones of high pressure and where temperatures (ion velocities) are reckoned in tens of millions of degrees.

On earth, extreme conditions of heat and pressure exist only at very great depths, and do not come anywhere near the required degree. At present, an impressively broad research programme is being carried out in the most advanced nuclear countries: in the U.S. and the U.S.S.R. since 1951, in Britain, and, for the last few years, in France, fundamental research into this subject has been progressing on several fronts. The technique to which most attention is being paid is that of passing high intensity electrical discharges through tubes containing gases (heavy hydrogen) at low pressures. These result in the production of several complex phenomena, difficult to analyse, but which are yielding information on the behaviour of what has been called the 'fourth state of matter' or 'plasma,' which is a substance composed essentially of free ions. The laws which regulate these reactions are those of magneto-hydrodynamics, a new and most complex chapter of modern physics.

Some apparatus enabled researchers to reach temperatures of several million degrees and produce fairly intense neutron emissions.[1] It was prematurely believed that the thermonuclear stage had already been reached, whereas theory says that the temperature must rise to about 100,000,000 degrees before effective thermonuclear reactions can set in. The complexity of the techniques that must be used is an obstacle to rapid progress. The stages are long and costly because the apparatus for thermo-

1. The Livermore Laboratory (U.S.) reported that temperatures around 35,000,000 °C had been reached and maintained for one-thousandth of a second with a piece of thermonuclear apparatus called a mirror machine (November, 1960). In Russia 12,000,000° C was achieved in 1 cubic millimetre of deuterium in 1961.

nuclear experiments is getting larger, and demands funds available only to some national laboratories.

This work, which was classified when the first Geneva Conference on the Peaceful Applications of Nuclear Energy was held in 1955, was disclosed and declassified at and since the second Geneva Conference in 1958. It is estimated that 20 years will be needed to obtain the full knowledge of thermonuclear processes and develop a power-producing thermonuclear reactor.

Once the process is discovered, if ever, one single thermonuclear power-station could be built to supply the whole of a country like France with electrical energy, using for its fuel a few pounds a year of deuterium, thousands of millions of tons of which is contained in the rivers and the oceans and is easily extractable.

But it is not known whether these possibilities can be realized with the material means and the knowledge of this day and age. The fire of the stars, which men have stolen to make the most sinister weapon ever conceived, may one day become our slave, but like Aladdin with the genie of the lamp, we would always go in fear of a change of temper.

6

Nuclear Propulsion

NEXT to the production of energy, the most fascinating aspect of atomic power is the possibility of applying it to propulsion.

To drive a heavy vehicle on the ground, in and under the water, and in the air is a triumph of human ingenuity. For thousands of years the power of marine currents, the power of the wind in the sails, and the muscular strength of rowers provided the energy required for movement. From 1820 onward, steam power began to supply a new source of energy, but hardly 100 years have gone by since engines have come into widespread use.

As the size of these engines was reduced and their power increased, they could be used in progressively smaller machines. The enormous boilers of the steamers foreshadowed the diesel engine, while the petrol engine made manned flight possible. The problem was the same at the beginning of the nuclear era. However, it is possible to reduce the volume of a reactor to a considerable extent and still draw from it an enormous amount of energy. Nevertheless, the bulk of such a reactor remains large, and in these conditions it was obvious that nuclear propulsion would first be applied to shipping, since a boat can carry a fairly heavy mass. A nuclear reactor and its protective shells account for a weight of several thousand tons.

NUCLEAR NAVIES

But the logical development of nuclear propulsion was reversed for a time, since the submarine was first chosen for the installation of a smaller, lighter nuclear reactor.

The achievement of this reduction in size and weight was the main object of research work started in 1947 by a team of U.S. researchers. The account of this brilliant achievement [13] is most revealing, both from the scientific and from the human

viewpoints. From the very beginning the large number of technical difficulties was all the more frightening as each represented a step into the unknown—from the concept of the reactor itself to the method of construction—while the new materials and the special conditions under which submarine engines must operate posed additional problems. Apparently the development of a satisfactory motor was expected to involve the construction of several prototypes studied according to a stepped programme spread over a long period. But Admiral Rickover, leader of the team, decided to build just one prototype, Mark I. The Mark II motor would be installed directly in the submarine.

Trials of the Mark I motor began in the Idaho laboratories at the end of 1952 and full power operation was reached in June 1953. It was successful beyond all expectations in power delivered, total power produced, and in robustness of construction. Essential components of the engine were even assembled on a submarine sacrificed for the purpose and subjected to depth-charges in Chesapeake Bay. This was to determine whether the mechanisms would stand up to battle conditions and to the heavy demands made on the motor of the future nuclear submarine under attack.

This motor is simple in its principle. A highly enriched uranium core is moderated and cooled by ultra-pure ordinary water under pressure. The heat is transferred, in a heat exchanger, to a secondary water circuit which turns into steam and this is used to drive two turbines. The latter drive one propeller each via reduction gears.

Nautilus was the name of the first submarine to receive this nuclear engine. It was built between 1952 and 1954 and its maiden voyage began on January 17, 1955. It is 315 feet long and 28 feet wide, displaces 3180 tons, and cost 90,000,000 dollars. We will not list the records broken by this marvellous piece of engineering, nor its feats of endurance apart from its passage under the ice-pack of the North Pole in 1958.

The first cruise lasted more than two years and the fuel charge was not changed, while consumption amounted probably to only a few pounds. Moreover, it was disclosed at the second Geneva Conference that the reactor maintains a steady power output because its fuel includes nuclear 'poisons.' When an ordinary reactor is operating, fission products are formed, some of

which absorb large amounts of neutrons, which means that the reactivity of the reactor tends to decline (reactivity being a measure of the amount of the possible departure of the reactor from the critical condition). The ingenious solution of this problem for the submarine motor was to add neutron-absorbing poisons (hafnium, boron, and other substances with a high-cross-section to neutrons) to the fresh fuel charge, so that from the start of operation these materials would absorb neutrons and be transmuted into other, less 'neutron-hungry,' isotopes. The poisoning effect due to their presence would thus decline, while simultaneously the poisoning effect from the fission products resulting from the burning of the fuel would increase. The two opposing effects would largely cancel each other out, so that the core would operate more uniformly from the beginning to the end of its useful life.

Each two to three years the core of the reactor is replaced and this requires a long period in dock at the Groton (Connecticut) base. Meanwhile, a new type of reactor has been devised which can be refuelled at sea. The first *Nautilus* core which operated from 1955 to 1957 permitted the vessel to cover 68,000 miles. The second (1957 to 1959) was changed after 94,000 miles, and the third is expected to give 140,000 miles.

The motor of the *Seawolf*, the second nuclear submarine, which used liquid sodium coolant, was entirely removed, cased in concrete, and sunk in one of the Atlantic deeps ([14] p. 77). This motor enabled it to cover 70,000 miles, like the *Nautilus* motor with the first core, but it was replaced by a pressurized water reactor of improved design whose components can be serviced at sea, while the sodium-cooled reactor was hermetically sealed. The new reactor is one of eight types studied by the U.S. Navy.

The U.S. fleet of nuclear submarines is increasing rapidly and will number 30 units by 1962. Among the first operational units and those commissioned by the end of 1960 were:

Nautilus	*Scorpion*
Seawolf	*Tullibee*
Skate	*George Washington*
Swordfish	*Patrick Henry*
Sargo	*Robert E. Lee*
Seadragon	*Triton*
Skipjack	*Halibut*

The *Triton* deserves a special mention because it is a very large submarine, 442 feet long, displacing 5900 tons, and driven by two reactors instead of a single one. The core of each reactor can be changed at sea.

Between the end of 1960 and September 1961 the following units were commissioned:

Scamp	*Thresher*	*Abraham Lincoln*
Sculpin	*Theodore Roosevelt*	*Ethan Allen*
Shark		

Under construction at September 1961 were another 14 killer submarines and 23 ballistic-missile submarines. It is anticipated that this fleet will be increased to 75 killer submarines and 40 to 50 missile-carrying submarines by 1970 [14].

The advantages of nuclear propulsion are self-evident. With it, a vessel can cover 125,000 miles on a few pounds of fuel, while the diesel oil needed for such a cruise by conventional vessels would amount to seven or eight times the weight of the submarine itself. There is also the fact that dives can be prolonged at will (*Triton* cruised round the world submerged from February 16 to May 10, 1960) as there are no batteries to be recharged and no motors depending on chemical combustion. Finally, speed: according to [14] *Skipjack* can do 38 knots *submerged*, and even higher speeds have been reported.

SURFACE VESSELS

The U.S. Navy has not concentrated solely on submarines and has built or is building:

The *Long Beach*, a 14,000-ton cruiser launched in July 1959, driven by two reactors and expected to reach 30 knots.

The *Enterprise*, a giant aircraft carrier of 86,000 tons, 1100 feet long, and propelled by a total of eight pressurized-water reactors, each developing 35,000 h.p. These reactors, like those of the *Long Beach*, will be able to operate five years without being dismantled or refuelled. Their cores are so complicated that each one takes eighteen weeks just to assemble. The total cost of *Enterprise* is put at 430,000,000 dollars. Another giant carrier is on the stocks.

The *Bainbridge*, a 7900-ton destroyer, is the smallest nuclear-driven surface vessel. Another destroyer has also been authorized.

Nuclear Merchantmen

Programmes for the construction of merchant navy vessels driven by nuclear fission energy are far behind military achievements. The Soviet Union has built the ice-breaker *Lenin* driven by three reactors, while the U.S. has launched the *Savannah*, a passenger/cargo vessel, which uses a single reactor.

The *Lenin* is the first civilian vessel to be driven by nuclear power. Construction began in 1954. It was launched in 1957, and the maiden voyage began in September 1959. The *Lenin* is an ice-breaker equipped with three reactors [15]. It is capable of cruising for one year without refuelling, displaces 16,000 tons, is 440 feet long, 90·5 feet wide, and has a total horsepower of 44,000. Speed in the open sea is 28 knots, and two knots in ice 8 feet thick.

The reactor block weighs 3017 tons, and the propulsion mechanism, including turbo-generators, 2750 tons. The reactors are of the pressurized-water type, fuelled with enriched uranium and using high-purity water under a pressure of 200 atmospheres.

Water enters the core at 235°C, and leaves at 248°C. It gives up some of this heat in an exchanger to water at 28 atmospheres pressure, and raises the temperature of the latter to 310°C. The steam thus produced drives turbo-generators.

The first *Savannah* was a small ship, displacing only 320 tons, which left Savannah, Georgia, on May 22, 1819, and arrived in Liverpool, England, 29 days and 11 hours later. Most of the voyage was made under sail, but for 89 hours, spread over seven days, the vessel was driven by a steam engine (the amount of fuel was very limited). It was the first time a ship had been propelled by steam for a part of its voyage, only 12 years after Fulton had demonstrated a steam-propelled ship, the *Clermont*, in a run up the Hudson River from New York to Albany (August 1807).

It was thus logical to call the first merchant navy ship for passengers and cargo the n.s. *Savannah* (n.s.=nuclear ship). The *Savannah* displaces 22,000 tons, and can take 9500 tons of cargo, and 60 cabin-class passengers. It is 584 feet long, 75 feet wide, and is expected to cost some 45,000,000 dollars.

The reactor vessel measures 4 feet in diameter by 5 feet 4 inches high [16, 17, 18]. The core will develop 74,000 kilowatts

(heat) and will consist of 8060 kilogrammes of uranium oxide enriched to 4·4 per cent. in U-235. Total content of fissile isotope will then be about 312 kilogrammes, of which some 50 can be burned. The vessel will be able to operate from three to four years without refuelling, covering a distance of around 335,000 miles (equivalent to 13 times round the world), at a speed of 21 knots. Coal for a conventional ship covering this distance would amount to 190,000 tons. Meanwhile, some 18 kilogrammes of plutonium will be extracted from the core after use.

The reactor has 32 fuel elements, of 164 rods each, making 5248 rods in all. Each rod is filled with 130 pellets of uranium oxide, giving a total of 682,240 pellets. It could be said that the vessel will consume two pellets per mile. The propulsion machinery develops 20,000 horsepower.

Moderated and cooled by pure ordinary water in a primary circuit, the flow through the core amounts to 1500 litres per second at 130 atmospheres. Water enters at 257°C and leaves at 271°C. A secondary water/steam circuit drives the turbines.

The reactor and its cooling circuits are enclosed in an enormous steel shell weighing 275 tons, the whole encased in a reinforced concrete protective structure weighing 1060 tons.

Nuclear Aircraft

Aerial propulsion by nuclear energy has met with considerable difficulties, not the least of which is the mass of the nuclear system, especially of its radiation shielding. There is also the danger of a serious crash, which would result in the contamination of large areas with radioactive materials.

Research is actively being carried out in the United States according to a long-term programme. Radiation from an aerial reactor (1954) suspended from high pylons has been studied, while a bomber carrying an operating reactor made a number of trial flights (1956) to test personnel protection and manœuvrability. At the same time, a turbojet engine was operated by air heated in a reactor. More recently (October 19, 1960) successful ground tests were carried out on the Kiwi-A3 reactor by its designers, Los Alamos Scientific Laboratory. It is an unshielded reactor producing intense heat which is transferred to a jet of high-pressure hydrogen gas for rocket propulsion. The whole apparatus is placed on a platform carried on flanged wheels

which runs on a railway 2½ miles long in the Nevada desert testing area. The device is called Kiwi after the flightless New Zealand bird. Manufacturers in the U.S. are to tender for a nuclear rocket engine.

Nothing is known of Russia's programme. American sources reported that a nuclear plane was flying in the U.S.S.R. in 1959, while, at the end of that year, Moscow Radio spoke of a nuclear plane for 1960. However, no further announcement had been made by late 1961.

If rockets propelled by jets of gas heated in a reactor can be perfected, this will bring about a revolution in rocketry and oblige us to revise all our ideas on space travel. These are perhaps far-distant possibilities. Nevertheless, they may come about much more quickly than the forecasts predict, in conformity with the principle of the acceleration of progress which is being demonstrated every day.

Nuclear Locomotives

There have been several reports, all unofficial, that plans for the construction of nuclear locomotives were afoot.

This development is at the limit of current possibilities. Reactors are now available which have cores small enough to be carried on a goods wagon of normal dimensions. Production of electricity by turbines fed by a fluid heated in this core can also be achieved in a fairly restricted volume—submarine reactors satisfy these conditions. But the major obstacle which has so far prevented the consideration of such a project is weight, which would still be very great, especially that of the shielding. The reactor would have to be surrounded by a fairly thick radiation-absorbing shell of prohibitive mass—at least 200 tons. This would raise the overall weight of the nuclear engine to between 350 and 400 tons. It might be possible to cut out the electrical stage and drive the axles directly from the turbine, which would mean reducing the weight to 200 tons.

Thus, nuclear locomotives could be conceived at present as being very long—120 feet to 150 feet—with 8 to 14 axles and developing between 6000 and 8000 horsepower. They would be capable of pulling very long and heavy trains at speeds equal to those now achieved by electric traction.

Their advantages are obvious, and include complete fuel

autonomy, since they could travel up to 60,000 miles while using only a few pounds of uranium. In other words, on lines such as those of the Trans-Siberian Railway, the engine could accomplish five or six return journeys without refuelling. There would be no need for electrified lines, for power-stations and electricity sub-stations, or for coal and water supplies at regular intervals along the tracks.

These prospects improve still further if the possibility is considered of doing away with some of the shielding, operating the engine by remote control, and interposing goods wagons between it and the passenger coaches. At stopping points shelters could be built to stop the radiation from the engine.

However, all these considerations are highly speculative, and the economics of such projects are controversial. It would appear that a nuclear-powered engine would have to operate 24 hours out of 24, pulling gigantic goods trains on very long runs (across the U.S.S.R. or America) to be really economic.

Nuclear propulsion will probably be applied first on these long-distance routes, but only after stringent experiments on the effects of vibration on reactor structure and, of course, after the complete elimination of all risks of derailments and collisions.

Atomic Lorries and Cars

Finally, a word about the possibility, often mooted, of one day driving road vehicles by nuclear energy.

The preceding chapters on propulsion through the fission of heavy elements make it obvious that in the present state of our knowledge such an application of nuclear energy would be quite impossible. There can be no question of replacing the engine of a motor-car by a small nuclear reactor, not because it would not be possible to build a reactor small enough—one day it might—but because the radiation that it would send out would always necessitate a minimum of 200 tons of shielding all around it. Further, a nuclear reactor is a device which produces a highly concentrated form of energy not compatible with the needs of a vehicle. Finally, the cost of a reactor will never come into line with that of an ordinary car. Power-stations and the propulsion of large masses would appear to be the limits of both fission and fusion reactors, whose energy is enormous when measured by the human scale.

Nuclear energy may not be limited to the only forms known at present—fission and fusion. We saw in an earlier chapter that the direct conversion of sub-atomic energy into an electric current was possible. If nuclear energy is ever to be used in small vehicles, it will be in this form. If it were possible one day to build accumulators which could take their charge from the disintegration of long half-life radioisotopes, then it would be possible to apply them to road vehicles, with the proviso that the question of cost would have been solved.

It is, nevertheless, legitimate to give rein to the imagination, and to anticipate a far-distant future when the technicians will have found new methods of releasing the energy contained in atomic nuclei. This is a possibility that must be reckoned with. Man will always be unable to pierce the veil of time which hides the discoveries of his descendants from his eyes, just as our own ancestors could not foretell the discoveries of the present day. The marvels of electricity were inconceivable to those living in 1760, and nuclear energy similarly to people of the 1860's. We know absolutely nothing of the discoveries of 2060, and we thus cannot deny that at some future date cars may run on a small engine no bigger than a child's balloon, which would last ten and even twenty years without being replaced.

It may be that to each human being at birth will be given an 'energy reserve,' which for the whole of his life will provide all the energy he will need to heat, light, and give power to his house and drive his vehicle. Domestic energy could quite simply be an ingenious use of ambient energy, that of the sun for instance, while that for the vehicle could come from nuclear power—only our descendants will know.

7

Utilizing Nuclear Explosions

THE energy set free by a nuclear or thermonuclear explosion is released in a fraction of a second, not taking into account the small percentage of the total which later becomes available as a result of the radioactive decay of the isotopes produced.

This energy is expressed as the weight of TNT needed to produce an equivalent explosion; a nuclear bomb such as that which destroyed Hiroshima is equivalent in power to 20,000 tons of TNT, or 20 kilotons. A very powerful explosion such as those at Bikini in 1954 will be measured in megatons—equivalent to the energy set free by the explosion of millions of tons of TNT. Such energy can also be expressed in kilowatt-hours and the conversion is as follows:

17·5 kt=20,000,000 kWh

Thus the explosion of a very powerful thermonuclear weapon, of which two or three were tested in recent years (about 20 megatons), releases an energy of 24,000,000,000 kilowatt-hours, or about half the electrical energy produced in one year by a country the size of France.

The total of 246 explosions which took place between 1945 and 1958 aggregated 180 megatons, or about equal to all the electrical energy produced in one year by the United States, or again all the energy expended in ten years by countries like Belgium or Switzerland.

The idea was thus conceived of harnessing this energy in some way. Its cost would be very low in spite of the exorbitant cost of a bomb. The nuclear explosive and the bomb mechanism for a one-kiloton device are priced at 200,000 dollars, but the cost does not increase proportionately [19]; 500,000 dollars for 10 kilotons; 700,000 for 20 kilotons and 1,000,000 dollars for

megaton weapons. The cost of the bomb mechanism itself accounts for about half the total.

If the TNT value is replaced by the figure in kilowatt-hours, we arrive at prices of around one mill (one-thousandth of a dollar; seven mills=0·6*d.* (six-tenths of a penny)) per thermal kilowatt-hour for one-megaton explosions, or several times less than the present cost of an electrical kilowatt-hour. It is thus possible to imagine a plant that would draw from the heat released by the explosion of an H-bomb electricity at a cost equivalent to, or considerably less than, power from hydro-electric, thermal, and nuclear fission plants—a 10-megaton bomb would give heat at a cost of 0·1 mill per thermal kilowatt-hour.

All this is, of course, theory. We do not know how to transform this energy, released in a fraction of a second, into quasi-permanent energy which can be drawn on little by little. The only possible solution at present is to use explosions deep enough below ground to ensure that there will be no rapid escape of heat or radioactivity.

Experimental Underground Explosions

The first declassified experimental underground explosion of a nuclear bomb in the U.S. was that of September 19, 1957, in Nevada and code-named "Rainier."[1] Eleven others took place in the series of 32 explosions in September to October 1958, also in Nevada. A further series of tests was begun in Nevada in September, 1961.

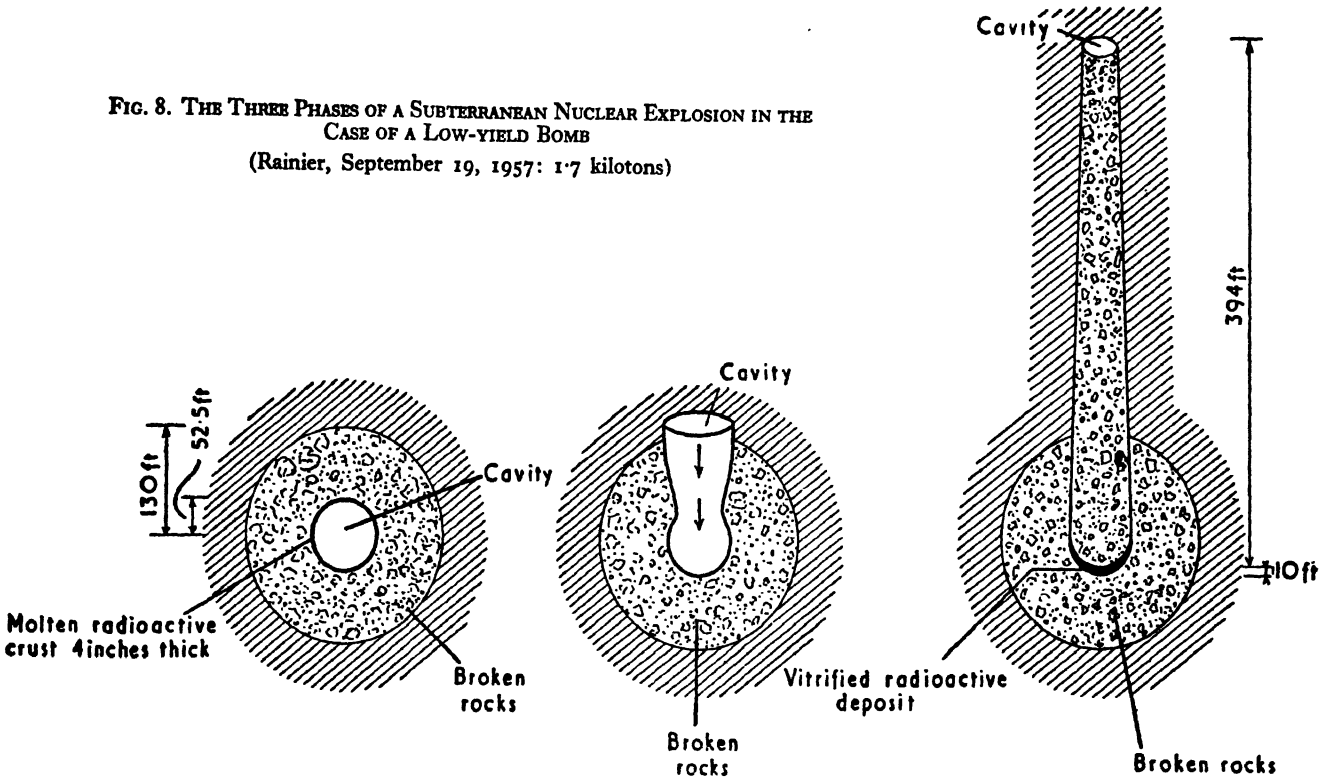
The "Rainier" shot [**20**] was a low-yield fission bomb—1·7 kilotons—buried under a mountain 920 feet below the summit, and exploded in a chamber 6 feet by 6 feet by 6·5 feet carved out in rock of density 2, and containing 15 per cent. to 20 per cent. water by weight.

When the shot was fired, the surrounding rock was compressed, raised to high temperature, and forced away from the centre, leaving a spherical cavity of a radius of 52·5 feet, walled with a layer of 700 tons of molten rock 4 inches thick, at a temperature of 1500°C, and highly radioactive. Outside the sphere in a radius of 130 feet, some 200,000 tons of rock were crushed and broken (Fig. 8).

[1] There was one "classified": "Uncle" of November 30, 1951, at 17 feet under the surface, 1·2 kt.

FIG. 8. THE THREE PHASES OF A SUBTERRANEAN NUCLEAR EXPLOSION IN THE CASE OF A LOW-YIELD BOMB

(Rainier, September 19, 1957: 1·7 kilotons)



An instant later the molten layer fell into the cavity, followed by a cone of crushed rock which filled the cavity now carpeted with a 10-ft-thick layer of vitrified and highly radioactive rock. The summit of the cone, marked by a small depression, was 394 feet above the explosion centre.

Three tunnels were excavated a long time after the explosion (two to three months, it appears) and the temperature was still 90°C 33 feet above the centre of the explosion. In the tunnel, at 59 feet, it was 47°C, and fell to the normal temperature of 17°C only at 98 feet from the centre. Towards the centre the temperature dropped because of conduction effects and the presence of water vapour which diffused into the crushed rock, taking part of the central heat with it. In 1961 the chamber was explored. Its radioactivity persisted, but at a low level.

Applications

These results indicate how such explosions could be used. First, in the crushing of enormous quantities of ore: a 100-kiloton bomb could break up some 50,000,000 tons of rock. Together with site preparation, it would cost around 1,000,000 dollars, so that each ton of crushed rock would cost only a very few cents. This mechanical application to copper ores and any low-grade ores would therefore be interesting.

On the heat-production side, the enormous quantity of thermal energy produced—nearly half the total yield—is to all intents and purposes stored for a long time around the focus of the explosion. In certain strata where water content is very low it might be possible to use explosions to produce 'heat stores.' One concept based on this would use two underground caverns blasted out by nuclear explosions, and link them by a passage in which a turbo-generator would be installed. An explosion in one cavern would heat the gases in it which would then be forced out into the second, driving the turbine and producing electricity on the way. A second explosion in the second cavern would reverse the operation.

The authors of this concept estimate that an explosion of a one-megaton bomb each week could feed an electrical installation with a capacity of 7,500,000 kilowatts (thermal). This would meet all the electric power needs of an advanced country with 40,000,000 inhabitants. They also claim that the cost of

power thus obtained would be no more than from conventional sources.

Another thermal application, and one somewhat similar, is the distillation of sea-water. A bomb would be used to produce a large cavity at a depth of more than a mile, sea-water would be pumped down, it would pass into steam and return to the surface as pure water. However, before this, an experiment called Project Gnome will be necessary. It will be the explosion of a 10-kiloton shot in the rock-salt deposits near Carlsbad, New Mexico, and will study the formation of radioisotopes and of new materials brought into being by the effects of very high temperatures and pressures not reproducible in the laboratory. The heat produced in these strata where there is no percolation of water will be tapped by a coolant, which will yield its heat to the turbines of a power-station on the surface.

Another mining application that has been studied in greater detail is that of extracting hydrocarbons from tar sands and from bituminous shale. The proposed experiment could be carried out at Green River, Colorado, where shale deposits are estimated to contain 700,000,000,000 barrels of petroleum, which is 15 times the estimated exploitable reserves of the U.S. and double those of the whole world.

In the case of tar sands and worked-out wells, an explosion would provide the heat needed to liquefy the oil and make it possible to pump it out. The heat could be maintained by injecting oxygen and allowing some of the oil to burn.

In the case of bituminous shale, the temperature would have to be higher, at about 400°C instead of 100°C as for tar sands, which adds to the technical difficulties.

Tar sands would appear to be the better bet, especially as reserves are far greater than those of bituminous shale. A single Canadian tar-sand deposit contains 500,000,000,000 barrels of petroleum, inaccessible to current techniques, but which could be exploited by nuclear explosions and heat. All estimates made on the foregoing operations indicate that they would be economic.

A more spectacular application, code-named Operation Chariot, would employ the surface explosion of an H-bomb. It would take place in Alaska, between Cape Seppings and Cape Thompson above the Arctic Circle. This giant excavation would create a harbour to give access to near-by ore mines.

The excavating power of nuclear explosions is, of course, considerable. A 100-kiloton bomb leaves a crater 230 feet deep and 1200 feet wide if it explodes 65 feet below ground and thus displaces 2,600,000 cubic yards. A 10-megaton H-bomb exploded at the surface of a coral reef leaves a crater 328 feet deep and 5250 feet wide, displacing 130,000,000 cubic yards. A device of the same energy, but exploded 360 feet below the surface of the ground, would dig an even bigger crater—1050 feet in depth and 5580 feet in width.

All these applications appear promising, but will require much more study, apart from preliminary trials. A black shadow on this bright prospect inevitably is the radioactivity of the long half-life isotopes—those resulting from the bomb, and those induced in the surrounding materials by the flux of neutrons.

The five underground trials carried out in 1957 and 1958 (one of which was fairly powerful) made it possible to measure residual activity, but the diffusion of this activity must be followed for a long time to determine its ultimate effects and distribution.

In particular, the case of the proposal to build a harbour with an H-bomb blast is open to serious question. We know by observation of the Pacific H-bomb trials just how dirty these bombs are, because they project into the very high levels of the stratosphere enormous amounts of radioactive dust. These facts will be analysed in the third part of this book. Calculations have been carried out [21] on the activation of stable isotopes contained in soil by slow neutrons produced in an explosion. The activities of the 18 most abundant elements have been established, and account must be taken of the fact that in an H-bomb explosion the mass of neutrons released is of the order of 10 kilogrammes compared with one gramme for a 20-kiloton fission bomb. Moreover, the 'clean' fusion bomb of the future, though it will eliminate fission products, will produce five to six times more free neutrons and, consequently, proportionately more radioactive isotopes in its surroundings through neutron capture.

Before every 'useful' explosion, the chemical composition of the soil must be considered and especially the presence of water-courses and underground systems which could disseminate induced radioactivity.

8

Radioactivity around Atom Sites

NUCLEAR research centres, plutonium plants, and atomic power-stations are not hermetically sealed units which take nothing from and yield nothing to the world outside. Just like every industrial organization, these centres, plants, and stations need raw materials on which they operate. The end-products as well as waste from intermediate operations must leave the plants sooner or later. Moreover, during processing, some by-products must be discharged.

In chemical processing-plants, for instance, there is an influx of raw materials to be treated, carboys of acids, gas cylinders, various salts, vats of dyestuffs—and large amounts of water. At the end of operations which have transformed all these ingredients into a manufactured product, there will be waste gases to be released to the atmosphere, solid wastes to be dumped, and large quantities of liquid containing varying amounts of chemicals to be pumped into disposal networks.

All nuclear industries must come within the above cycle. A laboratory will take delivery of inert or radioactive materials, use them, study them, transform them, and then will have to reject all or part of its intake. A nuclear power-plant will operate just like a thermal plant. The latter swallows large amounts of coal and water; the coal and the oxygen of the atmosphere combine to provide heat which is carried away by the water vapour to drive the turbines. But the smoke must be evacuated through the chimney together with gaseous compounds such as carbon monoxide and dioxide. Cinders and clinker must be stored and periodically removed; the water does not circulate in a closed cycle, it returns to nature after condensation, as does the cooling water from the condensers.

In the case of the nuclear power-station, there is no coal, but there is uranium metal which 'burns' (in the widest sense) and

accumulates in itself fission products which are the wastes or cinders of this atomic combustion. All the other phases of operation are similar to those of the conventional station. The central furnace in which the combustion of the coal takes place has been replaced by a nuclear reactor in which neutrons cause the fission of the uranium-235 contained in the bars of natural uranium. Every 6 to 20 months the 80 to 140 tons of irradiated metal in the core must be withdrawn and the uranium in the fuel elements chemically treated. This is in order to extract the precious plutonium which will form the explosive charge of the bombs and also the fission products which reduce reactivity, so that the purified uranium can be recycled.

These are all complex chemical operations requiring large amounts of reagents and of water. They are all carried out on intensely radioactive materials, and hence by remote control. The waste from these operations must be most carefully extracted and stored for a very long time so that there cannot be any dangerous release.

Moreover, among the fission isotopes produced in the reactors there are radioactive gases; in particular iodine-131 (8-day half-life), xenon-133 (5·2-day half-life), and krypton-85 (10-year half-life). These have sometimes been released to the atmosphere. However, a number of interesting applications are being found for radioactive krypton.

In certain cases there is the problem of the cooling water from plutonium-producing reactors. It passes through the reactor core and is subjected to neutron bombardment. These neutrons induce radioactivity in the impurities in the water which remain even after filtration. This water cannot be stored for a long time and must be returned to its natural cycle.

In this way every nuclear site will inevitably produce greater or lesser amounts of radioactive matter including:

1. solids and liquids of very high radioactivity which must be stored; this case is given detailed treatment in the following chapter;
2. liquids of slight activity;
3. gases of slight activity.

Substances in these last two categories enter into the metabolic cycles and biological accumulation by plants and animals

in contact with such substances takes place automatically. Around each nuclear energy site there is, then, some diffusion of radioactivity. All precautions must be taken to prevent an increase in concentrations of radioactive material to levels beyond which there is danger for living organisms.

Since 1945 there has been a vast expansion in nuclear industry, and the danger from the spread of radioactivity has risen accordingly. Much work has been devoted to the health and safety aspects of nuclear operations, and the conclusions of the health and safety experts as well as governmental action to safeguard public health and interest are mandatory upon nuclear-plant operators.

Diffusion and Accumulation of Activity

Here are three examples of the dissemination of radioactivity in air and by river water.

The first comes from a report published during the first Geneva Conference in 1955 [22]. The site under study is that at Hanford—an immense closed area in Washington State, U.S.A., where the nation's major plutonium facilities are located—in operation since 1944. There are at least four reactors, and probably more since 1950, each of 250,000 thermal kilowatts. All the chemical treatment of the uranium rods, the extraction of plutonium, and the storage of high-activity waste is carried out in this area through which flows the Columbia River. The reactors are cooled by water drawn from and pumped back into the Columbia.

The report describes analyses of heavy concentrations of radioactive substances found in aquatic and terrestrial animals caught in this area. Three categories of isotopes are examined: phosphorus-32 (14-day half-life), emitter of a 1·70 MeV (maximum) beta particle and produced by activation of the phosphates in the river water; fission products in general; and finally iodine-131 (8-day half-life), emitter of four betas of 0·81, 0·61, 0·33, and 0·25 MeV and six gammas of 0·08 to 0·72 MeV, the most abundant being that of 0·36 MeV (87 per cent.).

Phosphorus-32 is readily accumulated in relatively large amounts by micro-organisms and aquatic plants. Animals also absorb and accumulate this radioisotope. The following table gives some idea of the astonishing concentrations found in

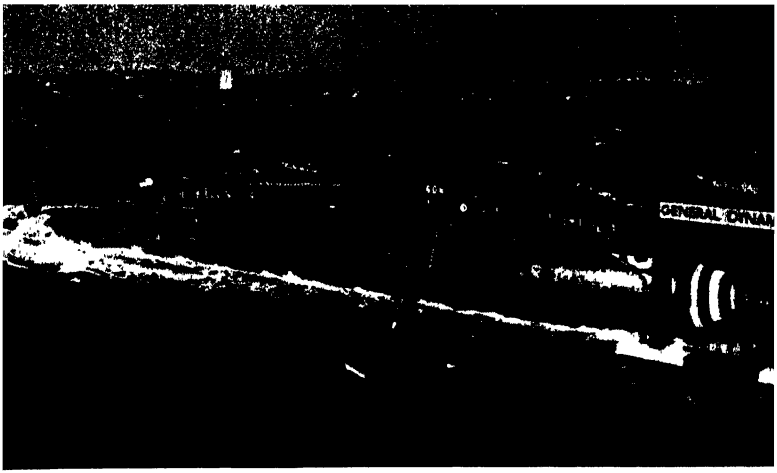
aquatic birds, the numbers indicating how many times more radioactive than the river water is the bird examined.

Species	*Food*	*Concentration (water = 1)*
Swallows		
Young	Insects	75,000
Adults	Insects	500,000
Ducks (*Aythya*)		
Adults	Insects, plants	50,000
Ducks (*Anas*) and Geese (*Branta*)		
Adults	Insects, plants, crustaceans	7,500
Young	Insects, plants, crustaceans	40,000
Yolks of eggs	—	1,500,000
Gulls (*Larus*)		
Adults	Fish, plants, crustaceans	5,000
Fish-eating Ducks (*Mergus*)		
Adults	Fish, crustaceans	2,500
Young	Fish, crustaceans	15,000

The remarkable aspect is the high power of concentration of these animals, the fact that the young show much greater concentrations than adults, and the fantastic factor for the yolks of the birds' eggs, of course normally rich in phosphorus. One thing missing in the table is the activity expressed in microcuries of these fowl, and if the proportions shown in the table shed an interesting light on the mechanism of this accumulation, they are meaningless as an indication of the real danger of the doses. This question was put at the end of the Geneva Conference session during which the report was read ([22] p. 392). "What is the concentration of radioactive materials in the Columbia River downstream from Hanford?" But the reply was that the speaker had not got the figures in his head and that they would be sent later to the questioner by letter. If we knew these figures, having the concentration factors, we would be able to calculate the radioactivity of the birds and see whether it is tolerable or far above the accepted levels.

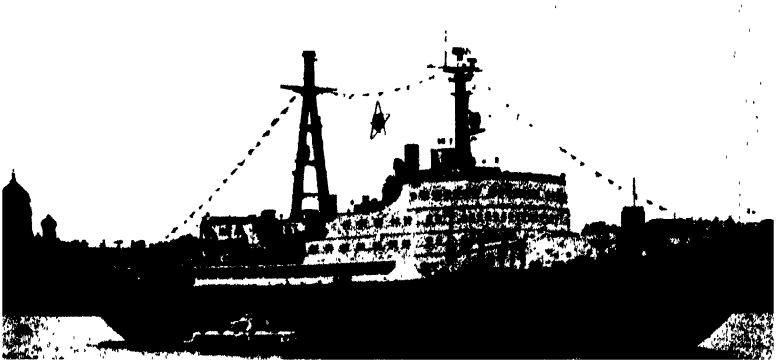
Nevertheless, the size of the concentration is by itself of primary importance and has been a major source of concern for the biologists in the face of the expansion of nuclear activities in the world.

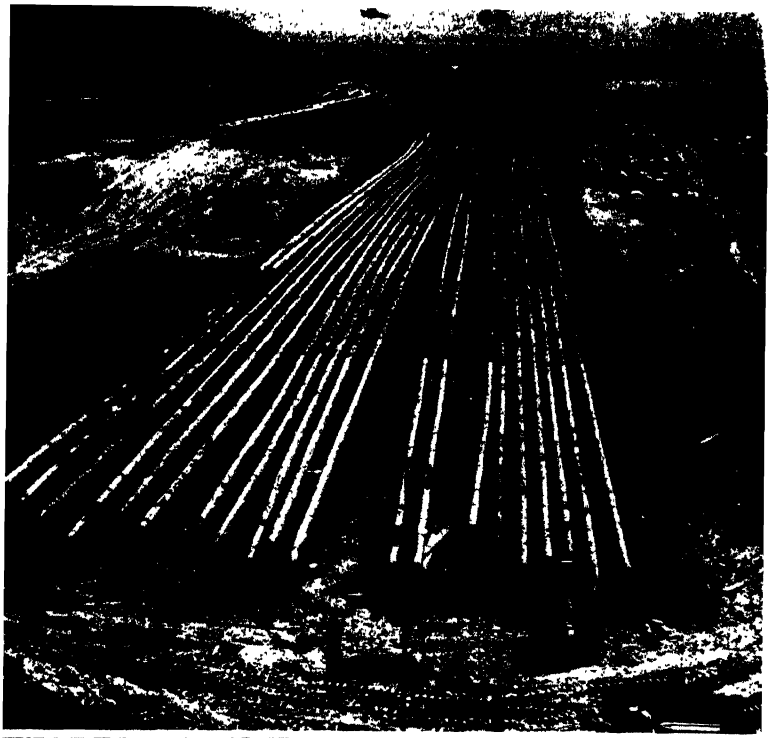
Waterhens which lived on a polluted lake for a period of four months were examined for radioactive content. The amount of

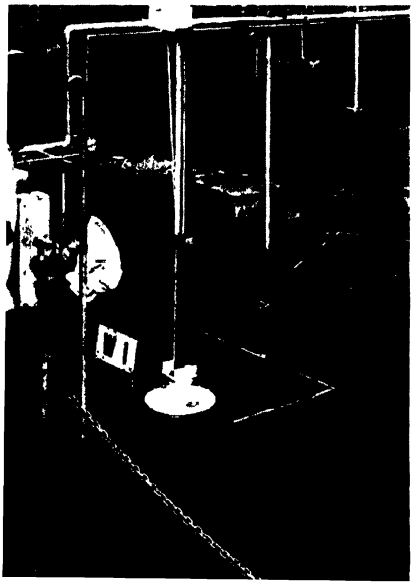


Launching of the "Ethan Allen," a nuclear submarine of the U.S. Navy. Costing 110,000,000 *dollars, it displaces* 6900 *tons and will carry the Polaris A-2 missile. It is believed to be the heaviest submarine so far built.*

The first civilian vessel to be driven by nuclear power was the Russian ice-breaker "Lenin." It displaces 16,000 *tons, and can cruise for a year without refuelling. It is seen here on the river Neva at Leningrad.*







(Above) *Low-activity radioactive waste can be released directly into the sea. This shows the laying of pipes which carry waste from the U.K. Atomic Energy Authority's nuclear power centre at Winfrith. The pipes extend two miles into the sea.*

(Left) *Radioactive materials are stored in underground tanks at the Oak Ridge National Laboratory, Tennessee. The tanks are connected to a chemical processing plant where usable radioisotopes*

radioactive contamination in the water being taken as unity, aquatic plants were found to contain 3, the flesh of the water-hens 260, and their bones 500. Among the fission products found were, of course, those with fairly long half-lives: ruthenium, caesium, and strontium/yttrium, the remainder being a mixture of rare-earth-group members. The concentrations were as follows:

	Ruthenium	*Strontium*	*Caesium*	*Rare Earths*
	%	%	%	%
Water	10	20	25	45
Vegetation	2	88	2	8
Flesh	—	—	90	10
Bones	—	60	20	20

This gives ample evidence of a remarkable 'filtering' effect that certain parts of living organisms have on some elements which we will find time and again in Chapters 16 and 17 dealing with fall-out.

The ducks that had access to the above-mentioned pond, but which did not live there regularly, accumulated far less radio-activity.

As for iodine-131, the problem is selective accumulation in the thyroid gland, and thyroids from various animals (especially hares) have been analysed to determine their I-131 content. In the case of hares caught round the site, the amount accumulated ranged from 100 to 1000 times the average content of the site vegetation. The average for the hares was 500 times this value. That for coyotes was five times less, and for reptiles ten times less. The thyroids of two-month-old leverets contained three times as much iodine-131 as those of adults, and, overall, there was a difference by a factor of ten between contents measured in January and in August.

The second example is that of the diffusion and concentration of zinc-65 through irrigation waters drawn from the Columbia. This isotope is also present in fall-out (see p. 199). Its origin has thus far not been satisfactorily explained, either as a component of fall-out, or as to its appearance in the Hanford cooling water. Its half-life is 246 days; it emits a positron of 0·32 MeV maximum and several gammas from 1·15 to 0·8 MeV.

The report [23] analyses the presence of zinc-65 in the food crops which grow on land irrigated by the waters of the Columbia, 30 miles downstream from Hanford—the water used by this

plant being only a minute fraction of the total flow. The samples were taken in July/August 1957. The pastures are continuously irrigated, fruits and vegetables intermittently. The next table gives concentrations in terms of micromicrocuries of Zn-65 per gramme of sample analysed, the concentration in the sample compared with river-water content being given in the second column.

It is clear that, apart from maize and grapes, which do not take up zinc, vegetables accumulate it in proportions from double to treble. Cattle take up one-twentieth of the zinc in the pasture

Samples	*Zn–65 content (micromicrocuries) per gramme)*	*Concentration factor (water = 1)*
Irrigation water	0·19	1
Pasture grasses	82·90	440
Beef (meat)	5·23	28
Beef (fat)	1·48	7·9
Cattle bones	5·80	31
Cows' milk	4·88	26
Peas	0·55	2·9
Tomatoes	0·46	2·4
Ketmia (Okra)	0·39	2·1
Green beans	0·29	1·5
Maize	0·16	0·83
Grapes	0·09	0·47

grasses (average of 25 against 440), but the concentration in grass being high, the values for the cattle are too.

In a bullock slaughtered in March 1959 which had grazed for one year on the irrigated pasture, the following quantities of zinc-65 were found, in micromicrocuries per gramme:

Meat	10·7	Pancreas	7·27
Fat	2·22	Blood	0·86
Bone	13·4	Hair	28·6
Hide	3·91	Thymus	3·79
Kidneys	5·98	Liver	11·5
Lungs	5·11	Horns	3·59
Brain	2·74	Hooves	2·59

Concentrations of radioactive zinc in the meat, the fat, and the bones of this animal were double those found in cattle slaughtered a year earlier, given in the first table.

To detect the presence of zinc-65 in humans, the authors of the report used a scintillation counter which enabled them to measure the total gamma activity of the body. Measurements made on a worker from the farm under study, who each day drank the local water, ate 100 grammes of the meat, and drank

700 grammes of the milk analysed above, showed that gamma activity due to zinc corresponded to 80,000 disintegrations per minute or 0·03 microcurie.

Twelve other persons, who did not live on the farm, but who drank water from the river, had activities from 5000 to 10,000 disintegrations per minute.

For yet other persons, who had no contact with these polluted waters, there was no positive evidence of the presence of zinc-65 in their bodies (see a more detailed analysis on this point in Chapter 17).

The authors of the report underlined the fact that the concentrations observed were far below the so-called 'tolerance' level for this isotope; 0·01 per cent. in the case of the farmer, and 5 per cent. for the pasture grasses. But it must be noted here, as in the technical summing-up, that to speak of one single isotope as being very much below the permitted dose is misleading, since several isotopes are present and, in the case of the humans studied in the report, a large number of isotopes were ingested simultaneously because of the existence of fission products in the Columbia water, plus radioactive fall-out.

The authors also reported the presence in the pastures of small amounts of chromium-51 and scandium-46. The former is a gamma emitter with a half-life of 28 days, while that of the latter is 84 days. Sc-46 is an emitter of two betas and several gammas.

The third report is one which studies the radioactivity of fish which live in an artificial lake near the Oak Ridge nuclear site, Tennessee, U.S.A. [24].

The Tennessee Valley has a grandiose sweep of dams along a 625-mile stretch of rivers from the Clinch to the Mississippi. In the higher reaches, towards Oak Ridge, the small White Oak Lake feeds the Clinch by way of a dam.

The report analyses the radioactivity of fish caught in the lake, and confirms the ban on fishing imposed in 1944. The fission product content of these fish, caesium in the flesh, strontium in the bones, is fairly high. In the Clinch, as it flows away from the site, the body content of the fish declines and greater quantities can be eaten. The content varies with the type of fish.

9

Radioactive Waste

THE most difficult problem of the atomic era is without doubt the so-called elimination of radioactive wastes. This in fact means their storage, for what is by nature indestructible cannot be eliminated. Because our earth has limits to its surface and volume, any radioactive waste thrown away on it will always be found again, diluted or concentrated, but intact in total. The only way to eliminate this material from the earth would be to fire it into space by rocket. But it will be a long time before this radical solution can be used; there is far too much waste and the technique would not be economic.

A chemical poison can always be decomposed; it is merely a more or less complex molecule which can easily be altered or dissociated into its component atoms. In the case of radioactivity, there is no solution. It is a phenomenon that is not influenced by chemical agencies or physical means because it belongs to the most inaccessible region of the atom, the nucleus, which can be reached only by nuclear means.

Once nuclear imbalance has been produced, a return to an unexcited state inevitably follows, accompanied by gamma radiation or the expulsion of a particle. Once fission has taken place, the numerous fission products will inevitably begin to disintegrate in their various ways.

This is what has been happening since 1945. The earth is becoming more and more impregnated with fission products brought down with the fall-out from fission bombs.

AMOUNT OF RADIOACTIVE WASTE

So far as the nuclear industry is concerned, the release of energy by the fission of large amounts of U-235 also results in the

creation of fission products and other radioactive isotopes which it is not possible to use at present and which, therefore, must be disposed of. At no time must these materials be allowed to come into contact with living things. This is the major problem of the handling of radioactive waste.

Feverish nuclear research activity throughout the world since 1942, the haste and incredible amplitude in the accumulation and testing of nuclear weapons, and the extraordinary expansion of a new-born nuclear industry, have already created an enormous potential of radioactivity.

Between 1945 and 1955 the main source of reactor fission products was the military production of plutonium in giant piles; there were also numerous research reactors. Since then, an increasing number of power reactors, though still comparatively few in 1960, have added a fraction to the total. A very rough estimate, but still within the right order of magnitude, is about 3,000,000 kilowatts for the average energy of nuclear plants in the four bomb-producing countries (with large nuclear capabilities) from 1945 to 1960. This corresponds to a total output of 25,000,000,000 kilowatt-hours of heat produced by the fission of 10 tons of uranium-235. In this way 10 tons of fission products were brought into being from 1945 to 1960. Apart from small amounts released to the biosphere, these have been stored.

The bomb explosions from 1945 to 1958 have created a total of five tons of fission products (see p. 219) spread around all over the world and in the atmoshpere. The twenty Soviet experiments between September 1 and October 5, 1961, added about 1 ton of fresh fission products.

These fission products, we know, have a continuously declining activity, and, after some years, only a few remain effective. Unfortunately, however, these are extremely harmful for a very long time. The total activity of 15 tons will still be about 15,000,000 curies in 100 years (the equivalent of 15 tons of radium).

The forecasts make these amounts look insignificant. By 1965 it is estimated [25] that the U.S.A. will have the equivalent of 11,000,000 kilowatts from all types, including 20 per cent. for naval reactors. This will mean a production of 10 kilogrammes of fission products daily. For the world, the figure for 1970 will be the equivalent of 25,000,000 to 30,000,000 kilowatts, creating some 10 tons of fission products annually.

Types of Waste

These fission products cannot be handled in amounts totalling the figures expressed above. To extract them from the sheets and cartridges of irradiated uranium, a long and difficult series of chemical processes must be undertaken, at the end of which the fission products are contained in large amounts of liquids and sludges which make disposal even more difficult.

Two cases must be examined: that of high enrichment fuel and that of natural uranium or slightly enriched fuel. The first step (up to the present) is to dissolve the irradiated fuel material in acids at the extraction plant. It is the liquid from this process that undergoes chemical treatment to extract the plutonium and the uranium.

Highly enriched fuels normally consist of alloys of uranium with zirconium, or aluminium, or stainless steel: the zirconium is extracted with fluorine and the stainless steel with sulphuric mixtures. However, the fluorine and sulphate ions remain in the radioactive waste liquids and attack the materials of the recipients in which they are stored. The remaining uranium is dissolved with nitric acid.

Natural or slightly enriched fuels are usually simply canned in magnesium alloy, aluminium, zirconium, or steel, these cans being removed before processing irradiated fuel (U.K. practice).

Thus, two types of liquid waste are produced:

1. Those due to the dissolving of the can, the zirconium by hydrochloric acid, and the steel by sulphuric acid. The resulting liquid is weakly radioactive with 0·1 per cent. fission products.
2. Those from the dissolving of uranium in nitric acid.

It is estimated that for one kilogramme of highly enriched uranium processed after irradiation, 500 litres of concentrated waste liquors are produced. In the case of natural or low-enrichment uranium, the figure is put at only 0·8 litre. Fuel from nuclear power-plants is expected to give 5 litres per kilogramme.

Of all the waste produced in these processes, one part is highly active, 100 parts are of medium activity, and 1000 parts are of low activity [26].

In 1970 the U.S.A. is expected to produce [27] 27,000,000

litres of solutions, and by the year 2000 more than 1,000,000 tons annually.

What happens to these three activities of liquid waste?

Liquid Waste Disposal

High Activity Wastes. Wastes in this category cannot be dispersed for many years. They must be stored in special tanks and kept there for at least one or two centuries, with the hope that some method will eventually be found to dispose of them in another way.

The quantities of liquids of this type, although much smaller than those in the other two categories, are already considerable, and since 1945 research workers have sought methods of concentrating them more and more to reduce their volume. But even if most of the nitric acid is eliminated, the waste cannot be concentrated more than 300 times, which still leaves a high total volume. From 1960 this volume is put at between 200 tons and 400 tons annually for Britain alone.

In the United States, one method has been tried which uses the heat produced in the solution by its intense radioactivity (one watt per litre) to provoke boiling and thus concentration. The first step is to concentrate by external heating to a volume of six to eight litres per kilogramme of irradiated uranium. The heat of disintegration is used to reduce volume by a factor between four and twenty.

However far concentration is carried, as a result of technical advances, large amounts of high-activity liquids will have to be stored indefinitely. In the U.S.A. the total quantity is expected to reach 600,000 tons by 1980, three times as much by 1990, and 12 times as much by 2000.

The presence of nitric acid and of fluorine, sulphate, and chlorine ions makes the choice of materials for storage tanks very difficult, because the high ambient temperature helps the solution to attack metal containers. The radiolytic decomposition of the water furthers this process, and can, moreover, cause formation of gaseous explosive mixtures if there is no ventilation. Furthermore, a condensation system must be provided to return radioactive water vapour to the containers. The tanks must be cooled by circulating water, and settlement of very highly radioactive sludges must be prevented.

All these technical problems and the construction of the appropriate containers in restricted zones contribute a large amount to the cost of nuclear energy based on fission.

Medium Activity Wastes. Much more abundant than the former, they result from later stages of the chemical treatment processes, and contain much smaller amounts of fission products. But they also contain large amounts of diverse chemicals added in the course of treatment which are a barrier to evaporation and concentration. Other means must be found to concentrate the active materials and separate them from the remainder, which then forms a third category of very low activity wastes.

Methods differ from country to country. In Britain these wastes are treated with chemicals which absorb the active materials and precipitate or flocculate, thus forming solids or semi-solids, with a concentration factor of about 200. There are other methods such as the use of gels or coagulants and of special filters.

All these products—precipitates, gels, and filtering materials —are then placed in sealed metal drums or concrete containers and buried in prohibited areas of atomic energy sites or sunk in the depths of the sea.

These processes are used in the U.S.A., too, but generally medium-activity waste liquids, and also those of low activity, are pumped into wells drilled in sedimentary soil which acts as a filter. This is the case at Hanford, Washington State, where the geological formation is highly suitable for this type of waste disposal. In ten years 1,000,000,000 litres have been treated in this way. The study of the infiltration of radioisotopes in the deep strata is carried out by drilling, which makes it possible to analyse their diffusion through the various types of rocks at a depth of some 300 feet, before they reach the water-bearing strata. From here, they must travel over a distance of several miles before reaching the Columbia River—a process expected to take about 50 years. By then the activity will be at a very low level and its dilution in the huge volume of water of this river will render it completely innocuous, according to the specialists. The drilling has helped to determine the speed of diffusion (ruthenium is a few months ahead of caesium, which itself precedes strontium).

Very Low Activity Wastes. These wastes are released into local rivers—the Thames for Harwell, the Rhône for Marcoule, the Columbia for Hanford—or directly into the sea as at Windscale and Winfrith in Britain. The dilution is strictly checked so that it cannot exceed the so-called 'permitted dose' as defined by international health and safety conventions.

The release of waste to the Irish Sea from Windscale is carefully followed, and has brought about much work on its dilution and distribution as well as on biological accumulation by marine organisms—fish, crustaceans, shellfish, seaweed, and plankton. As a result of this work some further limitations have been placed on the amounts discharged because it was found that marine algae tended to accumulate rather large amounts of activity. At Hanford, the volume of the releases initially permitted has been reduced because of the biological accumulation of radio-phosphorus (see Chapter 8) and of zinc-65.

Another method of waste disposal is to sink it in the sea. Between 1946 and 1957 the U.S.A. jettisoned in the Pacific [28] off the Californian coast 16,288 drums of 230 litres capacity containing slightly radioactive waste. Most of them were sunk south of the Farallon islands, but since 1953 some 2000 were dropped in the Santa Cruz basin, an undersea rift 5900 feet deep. Some 250 concrete blocks, also containing radioactive materials, or contaminated objects like the first motor of the *Seawolf*, were also disposed of in this way.

Oceanographers have protested against these actions. They assert that they cannot foresee what will happen to all these objects, or the paths their radioactive contents might follow around the oceans of the world, should the containers rupture under chemical and thermal effects.

Other Wastes

Other categories of waste must be noted:

Contaminated objects, such as the bodies of experimental animals which have been used in work with radioisotopes, also other solid wastes from many other activities.

Such wastes are incinerated, and the ash packed in metal or concrete containers for disposal at sea.

All the *radioactive products* used by laboratories, hospitals, and industry in the innumerable applications of radioisotopes in

medicine, pure research, and in tracer work. Most of these end up in the city sewers. In six months of 1956, the London hospitals alone used 70 curies of radioisotopes, of which 40 were eliminated in this way—the figures for the whole of Britain must be between two and three times higher. In the U.S.A. during 1954, of 1027 users of radioactive substances, 41 per cent. diluted them after use and poured them into the waste-water system, 40 per cent. kept them until after several half-lives the activity had almost ceased, while 19 per cent. cased them in concrete for sea disposal.

These sources of contamination are far from negligible in view of the rapidly growing numbers of applications and users throughout the world.

Gaseous wastes from reactors include krypton-85, xenon-133, bromine-82, and iodine-131. Krypton and xenon are noble, inert gases. Iodine could be emitted from an air-cooled reactor's stack should the scrubbing arrangements fail or be overwhelmed because of a number of fuel-element can leaks.

There is also carbon dioxide containing carbon-14, with a half-life of 5600 years, formed by the action of neutrons on the carbon dioxide coolant or the nitrogen of air-cooled piles.

To conclude, it is obvious from the facts given here that it is difficult to foresee the effect nuclear energy based on fission will have on the human race. For several years scientific circles have been at considerable variance on this matter, hampered though they may have been in expressing their views by the political and nationalistic import inevitably given to their work.

The physicists have discovered and perfected a marvellous and almost inexhaustible energy source. But its technical use is bound to bring about contamination, and this must be kept to a strict minimum by all the means now available to us.

At the same time the biologists, the oceanographers, the geneticists, and the geologists are full of foreboding on the consequences of this worldwide spread of radioactivity and its introduction into the life cycle.

There the question rests at present and the reader will by now have a better idea of the difficulty of deciding whether the atom, with its possible peaceful applications, is a friend or a foe.

10

Accidents on Land and Sea

EACH public and industrial application of nuclear energy gives rise to the possibility of an accident. The train drawn by a nuclear locomotive could be derailed; nuclear planes, or rockets, could crash to the ground, or explode in flight; a ship propelled by reactors could sink; a nuclear power-station could go out of control; and an atomic pile could release radioactive gases and dusts.

Insurance companies have done a lot of hard thinking about these possibilities[1] because they know that any accident could involve many people, and that as nuclear activities expand so do the chances of an accident. It is also known, still on the basis of statistical laws, that such occurrences certainly will happen. They will be due to a combination of numerous unforeseeable factors, which will only become known after the event.

The object of the present chapter is to examine two possibilities of major importance, an accident to a reactor on land and a nuclear shipwreck, since these are the two most probable events at present in view of the rapidly increasing numbers of reactors and of nuclear vessels.

ACCIDENTAL RELEASE OF RADIOACTIVITY FROM A REACTOR

This has happened in a serious form at least three times in Western countries—in the U.S., Canada, and in Britain. From the Eastern bloc there have been frequent, but unconfirmed, reports of a serious reactor accident in Russia in the Sverdlovsk area. The U.S. accident was the first known to involve fatalities (three, from explosive shock).

Windscale, England, is near the two Calder Hall power-

1. In Europe there is a Study Centre for Atomic Risks run by Comité Européen des Assurances, Zurich, Switzerland.

stations (see Fig. 7, p. 69), and here two huge reactors were built in 1949 to produce plutonium for atom bombs. It is thus the British equivalent of Hanford in the United States and Marcoule in France. At Windscale the two reactors were massive graphite-moderated blocks operating on natural uranium, like the Marcoule piles and those at Savannah River, U.S.A.

At Windscale the cooling of the two plutonium-producing reactors (which went into operation in 1950–51) was ensured by pumping air through the reactor core. After absorbing heat from the fuel cartridges, the hot air was evacuated through a 427-foot-high stack at the top of which a filter was installed to stop discharge of radioactive particles. Its effectiveness varied according to the size of the particles and the air throughput was enormous.

CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

A curious phenomenon of atomic physics is that known as *Wigner release*, named after the American theoretical physicist who forecast and studied the mechanics of this release before it was actually observed. Under neutron bombardment the crystalline structure of graphite changes, molecular cohesion is modified, and there is an accumulation of energy due to displacements of carbon atoms in the lattice, called Wigner energy. The temperature of the graphite must be raised considerably to permit these atoms to regain their places, whereupon they give up their energy with a further temperature rise.

The accumulation is important in low-temperature reactors, and if the energy were not deliberately released from time to time, a spontaneous uncontrolled and dangerous release could occur after a period of operation. In high temperature reactors, little or no Wigner energy accumulates.

A controlled Wigner release had taken place for reactor I at Windscale [**29**] by allowing the pile to operate at temperatures above normal and injecting heated air. This first operation was followed on October 10, 1957, by a second during which the accident occurred. Atmospheric analysis [**30**] at about half a mile from the reactor between 11 and 3 o'clock showed that radioactivity was ten times normal at 3000 beta disintegrations per cubic yard per minute. Other tests were made at 15 more points, and these confirmed that abnormal activity was spreading.

The first thought of the technical staff was that a uranium cartridge had burst, as had sometimes happened before. But a direct visual inspection of the reactor core showed that some cartridges were red hot! The core was on fire, and 150 channels containing uranium cartridges were affected. The uranium was burning in the stream of cooling air. (This could not happen at Hanford where cooling is by water, or at Marcoule where the coolant is carbon dioxide at 15 atmospheres pressure, or again at Calder Hall and in the British nuclear power-plants where the coolant is similarly carbon dioxide under pressure.)

The Windscale staff then attempted to eject the red-hot cartridges, but they had buckled and jammed. Those from adjacent channels were discharged to limit the risk that the fire would spread and cause further irradiated cartridges to burst. Meanwhile the 150 channels continued to burn. During the night the staff tried to stifle the blaze by pumping carbon dioxide into the central part of the reactor, but without success. Towards midnight the ultimate decision was taken—to flood the reactor. In the morning of October 11 at 8.55, staff began pumping large amounts of water into the core, and this continued for 24 hours until the core was cold and dead.

DIFFUSION AND COMPOSITION OF THE RADIOACTIVE CLOUD

From October 10 at about 11 o'clock to the following day at about 9—nearly 24 hours—an uncontrollable source of radioactive gas and dust released into the atmosphere via the reactor stack about 20,000 curies [31] of radioisotopes (the equivalent of 20 kilogrammes of radium). Some 5000 of these were deposited on the countryside between Windscale and a line running from St David's through Oxford to Cromer, a further 8000 fell on the remainder of Britain, while the remaining 7000 were shared by the rest of the world at the whim of the prevailing winds.

When the incident began, the wind at Windscale was blowing from the south-west. Shortly after it veered to the east and then back to south-west. At midnight a cold front moving up from the north-west drove the wind round to blow towards the south-east. Carried by the wind, the radioactive cloud then passed over the whole of England, including the London area, crossed the Channel, and was recorded at Mol in Belgium three hours

after it was recorded in London. The cloud then stretched 75 miles from Windscale, but spread over a width of 94 miles.

Measurements of this radioactivity were made in most countries by air filtration methods, and it was expressed in micromicrocuries per day per cubic metre. The maximum activity—1030—was recorded on Merseyside, followed by the Lake District with 728 to 803. When the cloud reached London in the morning of October 11, the figure was 431. Over Belgium the figure dropped to 49 in the Brussels area where the airstream split in two. Towards the south [32] observers recorded 2·7 at Paris, nothing in Spain, traces in Italy. To the east there was 0·2 at Zug (Switzerland), 1·0 at Vienna, and nothing in Czechoslovakia. To the north 31 was recorded at Eindhoven in Holland, 8·8 at Hanover, 2·7 at Potsdam, 1·9 at Sola (Norway), and 1·6 in Sweden [31].

A curious fact was that so much activity stayed in Britain; 13,000 curies against 7000 which crossed the Channel.

The radioactive cloud contained a mixture of radioisotopes, predominantly gaseous, iodine-131 and iodine-132 accounting for a major share. The analysis of the cloud made at Harwell [32], 225 miles from Windscale, on October 11 at 1 o'clock in the morning was as follows, the activity of the I-131 being taken arbitrarily as 100:

Isotope	*Half-life*	*Relative activity*
Iodine-131	8 days	100
Tellurium-132	77 hours	85
Iodine-132	2·3 hours	85
Caesium-137	30 years	11
Ruthenium-103	40 days	7
Polonium-210	135 days	2·6
Strontium-89	54 days	0·8
Strontium-90	28 years	0·04

Traces were also detected of ruthenium-106, zirconium-95, niobium-95, and cerium-144 [30].

Measurements of overall activities were made, and the totals for the major isotopes released into the atmosphere were [30]:

Iodine-131	20,000 curies
Caesium-137	600 curies
Strontium-89	80 curies
Strontium-90	9 curies

EXTENT OF POLLUTION

The above activities can be converted into masses. For caesium they represent 7 grammes, and for strontium 0·6 grammes.

A 20-kiloton atom bomb would produce about 60 grammes of each, and all the explosions up to the end of 1958 alone (see Conclusion) have produced between 160 and 300 kilogrammes of each of them. Pollution from Windscale is thus insignificant by comparison with worldwide fall-out. It was nonetheless spectacular as a first example of what might result from the peaceful applications of nuclear energy, especially as the site was in an inhabited zone and quite close to European countries with a high population density.

The British authorities lost no time in imposing stringent measures, including in particular a ban on the consumption of milk produced by cattle in an area of 200 square miles in a rough oval pointing south-east from Windscale. This ban, in force from October 12 to 30, was imposed because fairly high activities of iodine-131 were found in local milk at the outset (0·4 to 0·8 microcuries per litre).

An unprecedented number of measurements was carried out on milk, water, and farm produce all over the country. Iodine-131 was detected on October 11 in milk, drinking water, cattle, and even in the thyroid glands of adults and children living between 2 and 25 miles from Windscale, and the distribution was not homogeneous. At a distance of 11 miles, 12 adults had an average of 0·23 microcuries of iodine in their thyroids, and 11 children had 0·19, while $3\frac{3}{4}$ miles away, 3 adults had 0·11, and 2 children had 0·08. Some 23 miles from the site, tests on 5 adults gave an 0·09 average, and at 24 miles 9 adults averaged 0·16.

It was estimated that the integrated maximum dose of radiation for those adults with the highest thyroid burden was 9·5 rad and for children 16 rad. Measurements were also made on the strontium-90 and strontium-89 content of milk, vegetables, and pastures, immediately following the incident and for many months afterwards.

A series of relevant tests took place in the U.S.A. [33] on the iodine content of the thyroids of sheep slaughtered in Britain ten days after Windscale and sent to a research centre in

Tennessee. This centre three years earlier had begun an important research programme on radioactivity in sheep from the U.S.A., Britain, Germany, and Japan.

Before October 10, 1957, sheep from the London area had a thyroid content of one millimicrocurie of iodine-131 per gramme of gland, and those from the Tennessee area more than ten times as much (as a result of weapons trials in Nevada, over 1500 miles away).

By October 20 the figure for London had risen to 14–15, which was the average for Tennessee. Meanwhile, extremes of 55 were being recorded for the latter, as further U.S. tests were in progress. As for the German sheep (from Munich), their iodine content in November 1957 was barely 1 per cent. of that of U.S. sheep.

Reactor Number 1 at Windscale was partially dismantled and Reactor 2 stopped; a long inquiry was carried out on the exact technical causes of the accident, while the results of the inquiry were studied to prevent any recurrence.

The accident was the result of the second Wigner release; the first had proved non-homogeneous, and pockets of trapped energy had been left in the pile graphite. During the second operation, these pockets suddenly produced local temperature increases to 500°C.

International Concern about Accidents

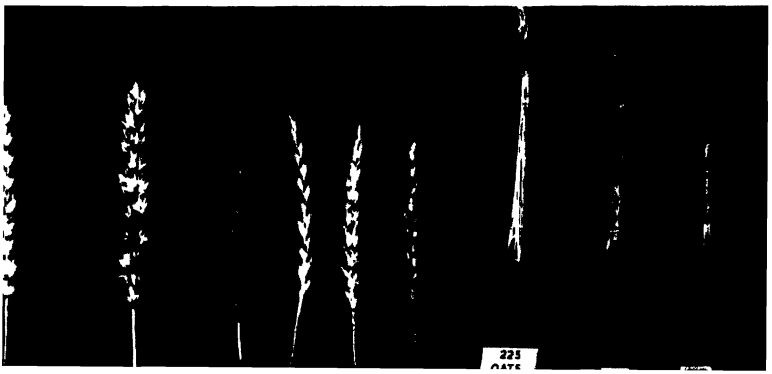
Since the nuclear industry is expected to expand very rapidly between 1966 and 1975 some countries are making a very detailed study of the legal and health and safety aspects of this expansion based both on experimental data and on theory.

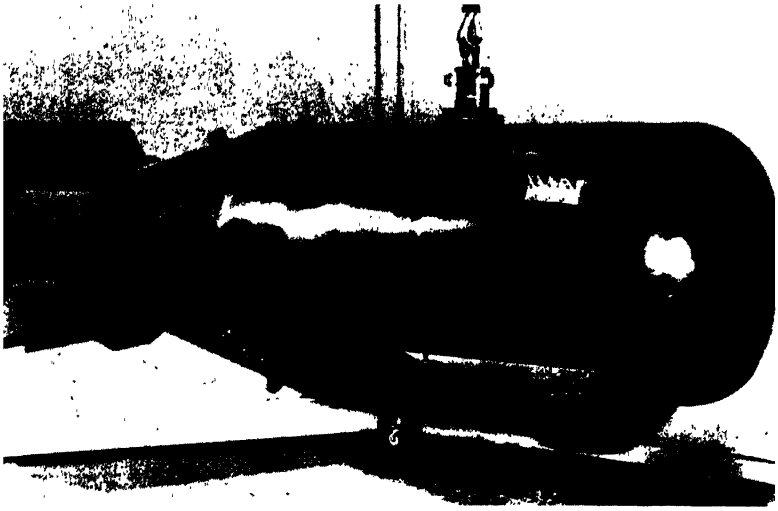
An interesting report along these lines was published at the second Geneva Conference in September 1958 [34] by the Dutch Royal Academy of Science. The report proposes a plan for a much more detailed study, and stresses how important it is for areas such as Europe to give due consideration to the future expansion of the nuclear industry.

The subdivision of the area into a number of countries, its high density of population, the high rainfall, the large number of rivers such as the Rhine, passing through several countries, the dense network of canals, the large number of ports and navigable waterways—all these factors make the possibility of land, or

The radiation emitted by radioisotopes can be used for therapeutic purposes. Here emission from caesium-137 is being employed in a London hospital.

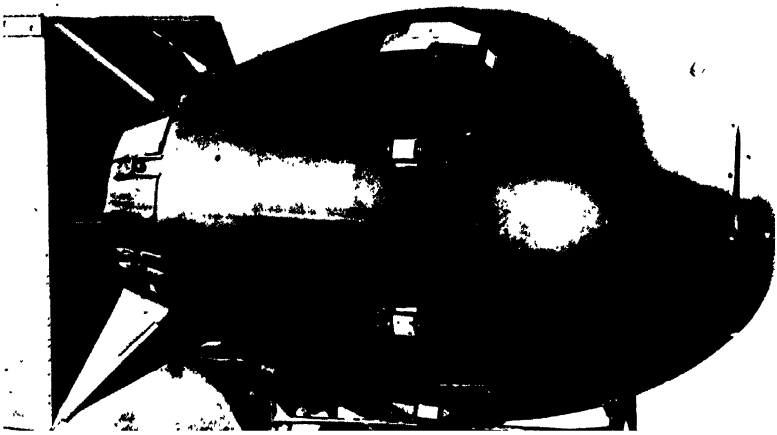
In agriculture the radiation from radioisotopes can be used to produce new strains of plant. These groups show some effects on wheat and oats. The ordinary strain, used as a starting-point, is on the left of each group.





The bomb that was dropped on Hiroshima on August 6, 1945. *Using uranium-*235, *it had a destructive power approximately equal to* 20,000 *tons of TNT* (20 *kt*). *It weighed about* 9000 *lb and was* 2 *ft* 4 *in across and* 10 *ft long.*

The bomb that was dropped on Nagasaki on August 9, 1945. *It had the same explosive power as the Hiroshima bomb, but employed plutonium instead of uranium. It was rather heavier* (10,000 *lb*) *and clumsier* (5 *ft across and* 10 *ft* 8 *in long*).



marine, reactor accidents a matter for grave concern. The diffusion of radioactivity by wind, rain, and rivers after such an accident would certainly be widespread and, consequently, there would always be a risk of spreading contamination from one country to others.

There are no frontiers for radioactive isotopes, and Belgians and Swedes breathed in the radio-iodine from Windscale in England.

The report enumerates briefly the sources of danger: nuclear reactors, plutonium extraction plants, stores of radioactive waste, industries using radioisotopes, future vehicles (ships, planes, and trains using reactors), and shipments of radioactive substances. For each type of accident, the consequences are all the more serious if nuclear energy is involved.

The diffusion of radioactivity can take place through wind dispersion, sea-water, rivers, lakes, and by transport vehicles. The report examines these possibilities and applies them to the particular case of the European continent.

Accidents apart, it points out that the aggregate effect of nuclear industries in many European countries will be to raise the general level of radioactivity in air and water. It concludes that international controls must be set up to limit as much as possible this inevitable increase.

Marine Accidents

Apart from the fact that the seas are becoming a vast 'atomic dustbin' for radioactive wastes, another matter is causing serious concern. It is the possibility of accidents to marine reactors.

Chapter 6 underlined the rapid increase in the number of nuclear-propelled vessels; reactors in naval vessels are expected to number about 50 by 1962, and this figure will be surpassed rapidly if all the projects for merchantmen are realized.

Meanwhile, insurance company reports show that accidents at sea follow the law of large numbers, and that the number of ships sunk each year is still fairly large, although it has been much reduced as a result of technical improvements in navigational aids.

It must therefore be expected that with the increase in the number of nuclear-propelled vessels there will be a proportionate increase in the probability of accidents. Nevertheless, this will

be much smaller than for conventional vessels, because the high cost of nuclear vessels, and the knowledge that they must not be wrecked, will oblige shipping companies to surround them with unprecedented precautions. It must then be concluded that no accident is likely to happen until the number of nuclear ships at sea is considerable.

There remains, of course, the element of chance and, in any case, even if the first accident does not take place in the immediate future, this does not mean it will not occur a few years hence.

An interesting analysis of the problem has been published [35]. The authors say the known programme of naval and civilian nuclear vessel building is big enough to justify a preliminary examination of the safety measures to be applied. The U.S.A., Norway, Britain, Sweden, West Germany, and Japan are building or considering plans for such vessels.

The basic question in a preliminary study is that of accidents, such as a collision between two vessels and a sinking with the possible release of radioactive materials. The mobility of ships, on the one hand, and the liquid medium which carries them, on the other, make the safety conditions for marine reactors very different from those for land-based units. Most nuclear propulsion plans for civilian purposes foresee fairly large units. But shipping statistics show that for vessels of more than 20,000 tons deadweight there are generally some seven accidents of greater or lesser importance each year. Three or four of these may take place near ports or in land-locked waters such as the Mediterranean or the Bay of San Francisco. When the nuclear vessel construction programme has reached its full development in 1970—according to the authors—one or two nuclear wrecks can be expected each year near inhabited countries.

This involves the mechanical risk of a spread of radioactive contamination to populated areas, which is similar to the risk of the effect of earthquakes or floods on a land-based reactor.

However, with a sea-borne plant there is another factor: the sea can completely stop or greatly accelerate the dispersion of radioactive products. Contamination of the seas is therefore an essential point to be considered. A nuclear merchantman needing 20,000 h.p. to propel it would require a 60,000-kilowatt (thermal) reactor. After a long period of operation, such a reactor

would reach a saturation level of six curies per watt, or a total radioactivity of 360,000,000 curies.

The study [35] supposes that all this activity is released, and uniformly dispersed, and calculates contamination expressed in ten-thousand-millionths (or 10^{-10}) of a curie per litre of water. The following table, extracted from the study, gives the name of the sea, its volume expressed as a multiple of 10^{17} litres, and the contamination in 10^{-10} curie per litre. These numbers relate to the activity of the fission products ten days after the stopping of the reactor.

Sea	*Volume* (10^{17} *litres*)	*Contamination* (10^{-10} *curie/litre*)
Pacific	707·00	0·0033
Atlantic	323·00	0·0073
Caribbean	9·50	0·25
Mediterranean and Black Sea	4·20	0·55
Red Sea	0·21	11·00
Baltic	0·02	102·00
Persian Gulf	0·006	392·00
San Francisco Bay	0·000076	22,400·00

Maximum permissible concentration in drinking water on this scale (10^{-10} curie per litre) is *one*, and this table shows, the authors assert, that for the Mediterranean and the Black Sea, half this figure would be reached; for the Red Sea, the Baltic, and the Persian Gulf it would be far surpassed; while for bays such as that of San Francisco it would reach considerable proportions.

These calculations obviously give rough orders of magnitude, which could not correspond to real conditions if only because ten days after the supposed accidental disintegration of the reactor dilution could not be uniform in seas such as the Mediterranean. Even if dissemination were very rapid, we know that according to the oceanographers there would never be uniform dilution, but that it would vary with the depth at which the wreck was lying, with local currents, and with zones of water and marine life.

However, there is one important point that the authors do not mention. The fission products are inside the bulk of the uranium fuel; some are short half-life radioactive gases (see Chapter 6) and can be ignored. Supposing that the accident resulted in a complete disintegration of the reactor core and a direct contact between sea-water and the metal sheath around the

fuel, it would take a long time for the sea-water to corrode the sheath and gain (limited) access to the fuel material to dissolve the dangerous fission products which would then be spread by the currents. The figures in this table are thus purely theoretical and have little contact with reality.

To get anywhere near the conditions supposed in the study, the reactor would have to explode shortly before or immediately after the postulated accident and melt as the water rushed in. This type of catastrophe is, of course, possible, and has been analysed in reports such as one presented at the first Geneva Conference (Document P.853, U.S.A.) [36]. A high-power reactor continues to emit a lot of energy, even after the nuclear reaction has been stopped, because of the presence of fission products whose radioactivity releases energy which is transformed into heat by absorption. This is often high enough to make it necessary to continue pumping the coolant through the core, otherwise temperatures might rise too much and the pile might be damaged. For a very high neutron flux Materials Testing Reactor, if the core temperature is 100°C one minute after the reactor is closed down, a complete coolant failure would result in an increase to 1000°C after ten minutes, and, if there were no melt-out, to 10,000°C after several hours.

But this rise of temperature after shut-down is most marked for a certain type of reactor, and though propulsion reactors would be of high flux, the temperature rise would be less marked. On the other hand, the effect sea-water would have on the hot graphite of a highly-rated, gas-cooled propulsion reactor might be catastrophic; while in heavy-water moderated and cooled reactors there could be an explosive reaction between uranium and water, which would add to any shipwreck damage.

These questions merit continued attention because all the technology of reactors is open to question. The marine nuclear propulsion programme obeys a number of rigid laws which are sometimes difficult to reconcile. Certain reactor types alone can be made light enough for the purpose, easy to control, long-lived, and of high power density. To this must be added safety requirements as to the type of materials used, leak-tightness, rigidity, use of coolants and moderators with low induced radioactivity. All these factors must now be taken into account in all the plans for future nuclear merchant ships.

The problem of nuclear navies is different and its importance is obvious to all. Since the aim of any conflict is to destroy or sink enemy units, the consequences of the mass destruction of nuclear submarines, cruisers, and aircraft-carriers are terrifying to contemplate.

PART III: THE FOE

II

Nuclear Bombs

BEFORE dealing with the worldwide and long-term effects of atom- and hydrogen-bomb tests, some general notes on these weapons are needed. These will cover:

1. the different types of weapon;
2. the test sites throughout the world;
3. the numbers of bombs exploded, and especially their power, with an assessment of the amount of contamination caused by them.

TYPES OF BOMB

Many different types of nuclear weapon have been developed by now, but it is not possible to give the exact characteristics of each of them because of military security. Nevertheless, for the past thirteen years there has been so much publicity around weapons trials, especially in the U.S.A., that the Press has published a mass of details often sufficient to give a rough idea of the types of weapon involved. The approximate power of the explosion is generally indicated.

Chapter 7 gave some idea of the terms used to express the power of A- and H-bombs. This is measured in tons of TNT (trinitrotoluene, the explosive with the highest blasting effect). For example, the Hiroshima bomb is said to have been a 20-kiloton weapon because the energy that it released in a fraction of a second was equal to that which would be released by the chemical explosion of 20,000 tons of TNT. But the effects of 20 kilotons (nuclear) are not the same as those of 20,000 one-ton bombs dropped on a town. The atom-bomb would destroy everything in an area the size of which would be dependent on the power of the bomb and the height at which it explodes, while

the 20,000 bombs would cause more widespread damage but would not cause total destruction.

The use of the term kiloton is a practical convention. In reality, energy is expressed quite otherwise in physics—in ergs, in kilowatt-hours, or in calories. If the 20-kiloton bomb is taken as a standard, or nominal, weapon, conversions are facilitated.

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20 kilotons

$=23$ million kilowatt-hours $(2{\cdot}3\times10^{7})$
$=830$ million million million ergs $(8{\cdot}3\times10^{20})$
$=20$ million million calories (2×10^{13})

This also corresponds to the complete fission of 1·15 kilogrammes of uranium-235, and to the annihilation of one gramme of matter according to Einstein's formula.

This table will be very useful later.

As we have read in Chapter 3, nuclear bombs are based on three principles:

1. The fission of a critical mass of the isotopes of heavy elements (uranium-233, uranium-235, and plutonium-239), this mass ranging from 5 to 20 kilogrammes or more. The fission of these complex nuclei releases energy and creates radioactive fission products.
2. The thermonuclear reaction, fusion (synthesis) of isotopes of light elements (hydrogen, deuterium, tritium, lithium) with release of energy and neutrons.
3. The fission by these high energy neutrons of the natural uranium (238) or thorium (232) tamper which surrounds the thermonuclear core. This type of bomb would be a fission-fusion-fission weapon.

At present all bombs are 'dirty' because they depend on fission, and therefore release enormous quantities of fission products. The 'clean' bomb is supposed to be one which does not use a fission bomb as a trigger for a thermonuclear reaction, that is, it would use conventional explosive to detonate a thermonuclear core. Such a weapon would not really be clean, and would eliminate from its fall-out only uranium fission products. There would still be large amounts of carbon-14, the metallic isotopes from the mechanical components of the bomb, the

remaining tritium, and other isotopes formed by fast and slow neutrons, as will be explained in Chapter 17.

If the energy released is taken as a criterion, the weapons can be classed in four categories:

1. those below 10 kilotons;
2. those between 10 and 500 kilotons;
3. those from 500 kilotons to 10 megatons (a megaton is equal to a million tons of TNT).
4. Those from 10 to 100 megatons.

The 'standard' bombs exploded at Alamogordo, Hiroshima, Nagasaki, and Bikini in 1945 and 1946 were about 20 kilotons. The improved weapons exploded at Eniwetok in 1948 were roughly between 20 and 50 kilotons.

Since 1950 research has concentrated on extending the range of energies both ways: towards bombs that are smaller than the standard one, and also towards the H-bombs which have energies from one hundred to one thousand times higher than the standard.

It is probable that fission bombs can be made to produce up to 80 kilotons, and that anything bigger must be a fission-fusion or a fission-fusion-fission bomb.

1. Bombs under 20 kilotons were apparently perfected in 1952, in particular for use with the nuclear shell fired up to about 12 miles by a heavy cannon. They are very small compared with their predecessors, since they can be fitted into shells 11 inches in diameter and weighing 660 pounds.

In 1956 still smaller devices were developed; we know that the Rainier shot was a 1·7 kiloton bomb.

On March 10, 1959, a communiqué of the U.S. Atomic Energy Commission [37] disclosed that eight of the trials carried out in Nevada during September and October 1958 were of weapons whose power was less than 1 kiloton. They were of 83 tons, 57 tons, 84 tons, 36 tons, 92 tons, 100 tons, and the smallest of only 6 tons. Three other shots were of approximately 1 ton; the least was "Titania" (October 30) of 0·15 ton.

These devices can be considered as small tactical weapons, whose carriers are handled and fired by only two men.

Thus, the nuclear weapon can be reduced to the power of the chemical bomb, since the largest blockbusters dropped from bombers during World War II were of 10 tons.

2. Medium-power weapons, or standard bombs, produced an energy of some 20 kilotons, and the actual yield of the charge was probably 2 per cent. only. It was quickly raised to about 6 per cent., and since then has doubtless reached much higher figures. It is probably possible to get from 50 to 100 kilotons from an ordinary A-bomb, or five times as much as the Hiroshima bomb.

3. From 1952 onwards the race for the H-bomb was on. Weapons were detonated at ground-level or on barges in and after November 1952, and especially in March 1954, with most unfortunate consequences. Power ranged from 5 to 15 megatons.

But the first real bombs of these energies—as distinct from unwieldy thermonuclear devices—to be carried in planes were tested in 1955 by the U.S.S.R., in 1956 by the U.S.A., and in 1957 by the U.K. Their explosive powers must have ranged from 1 to 20 megatons. They were bombs with a fission core, a thermonuclear inner envelope (deuteride of lithium and tritium), and an outer shell, or tamper, of metallic uranium or thorium.

The varieties of weapons within the various types are most diverse. Since 1945 the Americans have tested devices slung from balloons, subterranean mines, shells, medium-range rocket warheads, warheads for rockets exploding at altitudes between 30 and 300 miles, underwater torpedoes, a nuclear depth-charge exploded at very great depth, light anti-aircraft missiles, small and super-light weapons.

Nuclear Test Sites throughout the World

It is important to know the approximate areas in which explosions took place in order to determine how worldwide contamination by radioactive products occurs.

The map (Fig. 9) gives an idea of the spread of these sites. Numbers indicate a chronological order.

1. Alamogordo, near Los Alamos, New Mexico, U.S.A.; the first bomb (July 1945).
2. Hiroshima, August 6, 1945.
3. Nagasaki, August 9, 1945.
4. Bikini, Pacific, from 1946 onwards.
5. Eniwetok, Pacific, from 1948.
6. Irkutsk area, Siberia, U.S.S.R., and perhaps other sites on Soviet territory, from 1949. Includes Semipalatinsk, 1961.

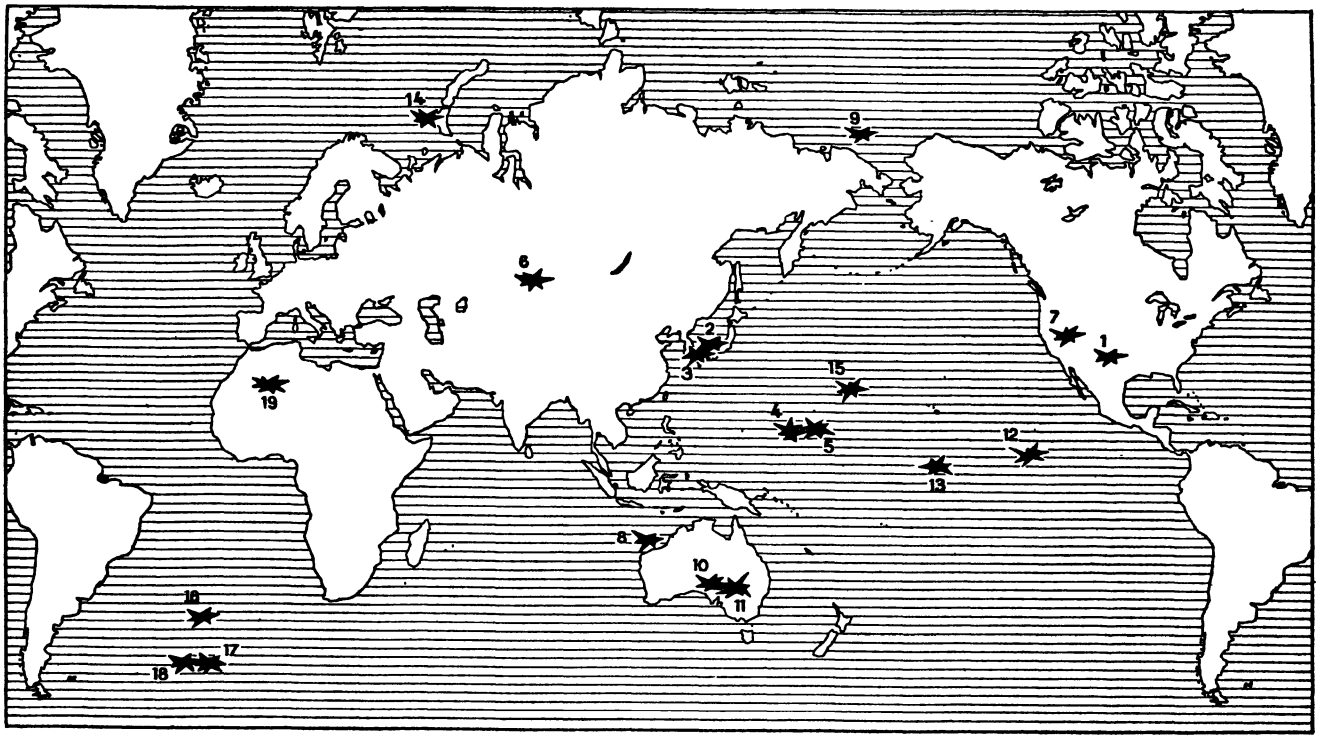


FIG. 9. WORLD SITES OF NUCLEAR EXPLOSIONS, 1945–61

7. Nevada trials ground, U.S.A., from 1951.
8. Monte-Bello Islands, Australia, October 3, 1953, and May 1956.
9. Wrangel Island, U.S.S.R. Detected by Japan.
10. Woomera, Australia, October 1953.
11. Maralinga, Australia, 1956.
12. An underwater explosion at great depth (U.S.A.), May 1955, and three in 1958, in the Pacific.
13. Christmas Island (U.K.), from the end of 1957.
14. Novaya Zemlya, U.S.S.R., from 1957? and September 1961.
15. Johnston Island (U.S.A.) two explosions at an altitude of some 60 miles, August 1958.
16, 17, and 18. Three explosions at about 300 miles altitude in the South Atlantic, August and September 1958.
19. French Sahara, 1960.

The dates of all the known weapons tests up to the time of going to press will be found in the next chapter.

The main lesson to be learned from this map is that explosions have taken place in all latitudes from the Arctic to the Equator but that the mean latitudes have borne the brunt of the experiments, as regards both the number of tests and the high aggregate energy released. This means that maximum concentration of fall-out is spread around the latitudes with the largest share of world population.

The Number of Tests and Total Energy

The exact number of tests must be guessed because not all the explosions have been listed by the U.S.A. and the U.S.S.R. Only Britain has given the exact number of trials.

The official number of tests, including the American tests announced by the A.E.C., the Soviet tests detected and announced by the A.E.C., and the British tests, was 207 at the end of October 1958 when the U.S. suspension was announced (plus two Soviet tests at the beginning of November). The following figures are taken from a United Press despatch of November 7, 1958 [38]. The dispatch says the figure of 207 is a minimum, and unofficial reports indicate as many as 246, as follows:

U.S.A.	131 (official)	or 154 (including unofficial)
U.S.S.R.	55 (official U.S.)	or 71 (including unofficial)
U.K.	21 (official)	21
Total	**207 (official only)**	**246 (including unofficial)**

Since this report the A.E.C. has indicated that 169 nuclear detonations were touched off by the United States since August 1945, compared with the figure of 131 listed in the past by the Commission. However, the shots in the latter list were "significant for one reason or another" while some among the total of 169 produced little or no nuclear explosive yield. The above figures should thus be amended to 245 (official) and 261 (unofficial).

But can one base an estimate of the worldwide spread of fall-out on such figures? The answer is obviously that one cannot, since each explosion creates greater or lesser amounts of fission products. What is needed is an idea of the fission energy released by all these explosions. For this we will use a table released on August 13, 1959, by the Joint Congressional Committee on Atomic Energy of the U.S.A. in the official report drafted for Congress, *Fall-out from Nuclear Weapons Tests* [39].

The table makes a distinction between total energy and energy due to fission alone, since it is the latter which gives the amount of fission products. It also differentiates between air-bursts, and ground-level and sea-level explosions. The figures cover the U.S.A., the U.S.S.R., and the U.K.

	Fission Energy (kt)			Total Energy (kt)	
	Air	*Ground*	*Water*	*Air*	*Surface*
1945–1951	190	500	20	190	570
1952–1954	1,000	15,000	22,000	1,000	59,000
1954–1956	5,600	1,500	6,000	11,000	17,000
1957–1958	31,000	4,400	4,600	57,000	28,000

This table shows that total energy (fission plus thermonuclear) was 173,760 kilotons, or roughly 174 megatons. Fission energy accounts for 91,810 kilotons, say 92 megatons. Of the total, the U.S.A. and Britain together are believed to be responsible for 66 megatons and the U.S.S.R. for 26 megatons. But it must be pointed out that the proportion fission/fusion has been taken rather arbitrarily at 1, which means that the shares of each in total production are taken to be equal, but this is far from certain. It would be better to take 180 megatons for the total, and 120 megatons for fission yield. Nevertheless, we will retain the Congressional report figures as a basis since the orders of magnitude alone are important.

They are eloquent enough! To say that 174 megatons of explosive nuclear energy have been released means that in 13 years 35 times more explosive has been detonated than during World War II when some 5,000,000 tons of bombs and shells were used. Air bombardment by U.S. forces in Europe and Asia during the war amounted to 2,000,000 tons. The 174 megatons represents 87 times this amount! It can be said that nuclear tests have set free more energy than all the explosions which have ever occurred on earth in war and in peace.

On the other hand, if the standard bomb is taken as 20 kilotons, the 174 megatons represent the equivalent of 8700 Hiroshima/Nagasaki bombs. From August 6, 1945, to October 31, 1958, there were 4470 days. Hence the net result was the same as if every day during those thirteen years, two bombs similar to those dropped on Japan had been exploded.

Finally, the radioactivity of the fission products must be considered. At the beginning of this chapter, we said 20 kilotons corresponded to the fission of 1·15 kilogrammes of uranium. A simple rule of three shows that 92 megatons corresponds to the fission of 5290 kilogrammes of uranium. This means that a fair proportion of five tons of fission products have been dispersed to the four winds, since although about half is quickly precipitated in the area around an explosion site the remainder is blown into the high atmosphere and comes back to earth in the form of fall-out. We will study what happens to this in later chapters.

12

Chronological List of Explosions

THE pages which follow are devoted to a table drawn up year by year from 1945 to 1961 of A-bomb and H-bomb explosions.

This list is not official and has no other source than long and patient perusal of daily newspapers, completed to a very small extent by a few official references (such as the Semi-Annual Reports to the U.S. Congress of the United States Atomic Energy Commission). For the U.S.A., the list is based on *Probing the Earth with Nuclear Explosives*, by D. T. Griggs and F. Press, UCRL 6013.

Up to and including 1959 three columns are devoted to the U.S., U.S.S.R., and U.K. explosions. In each column the explosion is marked, the date, and some information if available, sometimes the code-name of the experimental shot when it has been officially released (the H-bomb explosion of March 1, 1954, at Bikini, notorious because its rapid fall-out affected the Japanese fishing vessel *Fukuryu Maru*, was called "Bravo"!), and the series code-name is also given when possible. For 1960 onwards, a fourth column appears for France.

For the U.S.S.R. the major part of the data is uncertain. Often only Japanese reports have indicated the probability of an explosion, and a question mark should be placed after most of the dates indicated.

Yields are also estimated, generally on the basis of Press reports. It is nevertheless interesting to note that the total of the yields corresponds fairly well with the table on p. 127, from the report to Congress [39], including the grand total for 13 years—about 190 megatons. At the bottom of each column on the left is the estimated energy of the simple fission bombs, and on the right that of the composite H-explosions. A is the energy of the fission bombs and H that of the hydrogen bombs.

The tables contain some 220 explosions up to the end of 1958, which is a minimum to be compared with the data of Chapter 11 giving 207 (245) official and 246 (261) unofficial tests. As much information as possible has also been included for later tests.

This tabulation helps one to follow clearly the development of the atomic problem since 1945. Three stages are apparent:

1. 1945 to 1951—experiments are scientific in character and seek to perfect devices of conventional type.
2. From 1952 to 1955—emergence of the H-bomb. Trials were held to develop a bomb which could be transported and on possible variants.
3. 1956, 1957, and 1958. These are the three terrible years in which 140 tests were held against less than 100 for the 10 preceding years, producing nearly 140 megatons of energy against 190 megatons overall. All the weapons of war become nuclear as a result of research pushed to the limit, whereas the nuclear device at the beginning was an exceptional and rare means of intimidation.

	U.S.A.	*U.S.S.R.*	*U.K.*
1945 A (60 kt)	*Operation Trinity* July 16: 1st bomb (Pu) at Alamogordo 20 kt *Bombing of Japan* August 6: Hiroshima (U-235) 20 kt August 9: Nagasaki (Pu) 20 kt		
	60 kt		

	U.S.A.	*U.S.S.R.*	*U.K.*
1946 A (40 kt)	*Operation Crossroads* July 1: Bikini (air) "Able" 20 kt July 25: Bikini (underwater) "Baker" 20 kt		
	40 kt		

	U.S.A.	*U.S.S.R.*	*U.K.*
1947	NO EXPLOSIONS DETECTED		

	U.S.A.	*U.S.S.R.*	*U.K.*
1948 A (150 kt)	*Operation Sandstone* April 14 "X-ray" 36 kt April 30 "Yoke" 48 kt May 5 "Zebra" 18 kt		
	102 kt		

	U.S.A.	*U.S.S.R.*	*U.K.*
1949 A (50 kt)		July 14: first explosion detected 50 kt?	
		50 kt	

	U.S.A.	*U.S.S.R.*	*U.K.*
1950	NO EXPLOSIONS DETECTED	?	

	U.S.A.	*U.S.S.R.*	*U.K.*
1951 A (500 kt)	*Operation Ranger* (Air Drop) (Nevada I) January 26–27 1·8 kt, 8 kt February 1–2–6 1 kt, 8 kt, 22 kt Total: 40 kt *Operation Greenhouse* (Tower) (Eniwetok II) In April and May: 4 explosions including a detonator for a thermonuclear bomb Total 300 kt? *Operations Buster and Jangle* (Nevada II) October 23–28–30 0·1 kt, 3·5 kt, 14 kt November 2–6–21–30 21 kt, 31 kt, 1 kt, 1 kt (Nov. 30 was first underground) Total: 70 kt	September: second explosion detected October: third explosion detected	
	410 kt	80 kt	

	U.S.A.	*U.S.S.R.*	*U.K.*
1952 A (220 kt) H (5000 kt)	*Operations Tumbler and Snapper* (Nevada III) April 1–15–22 1 kt, 1 kt, 31 kt May 2–7–24 19 kt, 12 kt, 11 kt June 2–5 14 kt, 14 kt Total 103 kt *Operation Ivy* (Eniwetok III) November 1: "Mike" first three-stage bomb exploded at ground level 15,000 kt (minimum)[1] November 11: "King" ?		Monte Bello Islands (Australia) October 3: first explosion 20 kt?
	200 kt 15,000 kt		20 kt

1. 40,000 kt according to Japanese measurements.

	U.S.A.	*U.S.S.R.*	*U.K.*
1953 A (400 kt) H (1000 kt)	*Operations Upshot and Knothole* (Nevada IV) March 17–24 16 kt, 24 kt April 1–6–11–18–25 0·2 kt, 11 kt, 0·2 kt, 23 kt, 43 kt May 8–19–25 (first shell) 26 kt, 32 kt, 15 kt June 4 61 kt Total 250 kt	August 12: first H-bomb 1000 kt? August 23 (August 18 official announcement of a series)	Woomera (Australia) October 14–26 50 kt?
	250 kt	100 kt 1000 kt	50 kt

	U.S.A.	*U.S.S.R.*	*U.K.*
1954 A (not known) H (42,000 kt)	*Operation Castle* (Bikini-Eniwetok IV) Six large thermonuclear weapons March 1: "Bravo" (ground) 15,000 kt March 27: "Romeo" (barge) 6000 kt April 7: "Koon" (ground) ? April 26: "Union" (barge) 4000 kt May 5: "Yankee" (barge) 15,000 kt May 14: "Nectar" (barge) ?	H-Series announced September 15–19: Japanese detections; neptunium in fall-out indicating uranium tampers in fission-fusion-fission bombs October 25–31	
	40,000 kt	? 2000 kt	

	U.S.A.	*U.S.S.R.*	*U.K.*
1955 A (300 kt) H (3000 kt)	*Operation Teapot* (Nevada V) February 18–22 1·2 kt, 2·4 kt March 1–7–12–22–23 7 kt, 43 kt, 4 kt, 8 kt, 1 kt March 29(2) 14 kt, 3 kt May 6–9–15 (Doom City) 3 kt, 1·5 kt, 22 kt June 5–15 28 kt, 28 kt Total: 170 kt *Operation Wigwam* May 14: underwater explosion at great depth in Eastern Pacific 30 kt November: first series of safety tests in Nevada	July 4: a series in progress September 24 November 10–18–21: Japanese detections	
	300 kt	? 3000 kt	

	U.S.A.	*U.S.S.R.*	*U.K.*
1956 A (unknown) H (33,000 kt)	*Operation Redwing* (Eniwetok) 13 explosions May 4 "Lacrosse" (surface) May 20 "Cherokee" (first H-bomb from plane) 10,000 kt May 27 "Funi" (surface) May 30 "Erie' (tower) June 6 "Seminole" (surface) June 11 "Flathead" (barge) June 11 "Blackfoot" (tower) June 16 "Osage" (air drop) June 25 "Dakota" (barge) July 8 "Apache" (barge) July 10 "Navajo" (barge) July 20 "Tewa" (barge) July 21 "Huron" (barge) Total: 30,000 kt	January February } Foreign detections July: Japanese detection August 24–30 September 2–10 2000 kt October? November 17: rocket? December 14–19: Japanese detections	Monte Bello Islands (Australia) May 16: June 19: 50 kt? Maralinga (Australia) September 27: October 4–11: ? October 60 kt
	30,000 kt	3000 kt	110 kt

	U.S.A.	*U.S.S.R.*	*U.K.*
1957 A (At least 400 kt) H (54,000 kt)	*Operation "Plumbbob"* (Nevada VI) May 28 "Boltzman" 11·5 kt June 2 "Franklin" 0·14 kt June 5 "Lassen" 0·47 kt June 17 "Wilson" 10·3 kt June 24 "Priscilla" 36·6 kt July 5 "Hood" 74·3 kt July 15 "Diablo" 17 kt July 19 "John" (rocket) 2 kt July 24 "Kepler" 10·3 kt July 25 "Owens" 9·7 kt August 7 "Stokes" 19·1 kt August 10 "Saturn" ? August 18 "Shasta" 16·5 kt August 23 "Doppler" 10·7 kt August 30 "Franklin" 4·7 kt August 31 "Smoky" 44 kt September 2 "Galileo" 11·4 kt September 6 "Wheeler" 197 kt September 6 "Coulomb B" 0·3 kt September 8 "Laplace" ? September 14 "Fizeau" 11·1 kt September 16 "Newton" 12 kt September 19 "Rainier" 1·7 kt September 23 "Whitney" 18·5 kt September 28 "Charleston" 11·5 kt October 7 "Morgan" 8 kt Total: 330 kt	January 19 March 8 April 3–6–10–12–16–18–23—several H-bombs including one with thorium tamper 15,000 kt August 22: H rocket? 2000 kt? September 9: September 23–24–25: Naval manœuvres October 6–10 (H) 20,000 kt?	Christmas Island (Pacific) May 15: first H-bomb 1000 kt? May 31 5000 kt? June 19 5000 kt? Total: 12,000 kt? Maralinga (Australia) September 14 1 kt? September 25 1 kt? October 9: first balloon 20 kt? Christmas Island November 8: H-rocket? 2000 kt
	330 kt	? 40,000 kt?	22 kt? 14,000 kt?

	U.S.A.	*U.S.S.R.*	*U.K.*
1958 (At least 400 kt) H (52,000 kt)	*Operation "Hardtack I"* (Pacific) April 28 (balloon, 17 miles) May 5–11–11–12–16 (underwater, 500 ft)–20–21–26–26–30–31 June 2–8 (underwater, 150 ft)–10–14–14–17–27–27–28–29 July 1–2–5–12–22–22–26 August 1 (rocket 53 miles)–12 (rocket, 30 miles). Both at Johnston Islands *Operation "Argus"* (South Atlantic) August 27–30 September 6 All three at 300 miles altitude *Operation "Hardtack II"* (Nevada VII) (32 explosions of small yields, 11 underground) September 12–17–19–21–28–28–29 October 5–5–8–10–13–14–15–16 (2)–18(2)–22(3)–24 (2)–26 (3)–27–29 (2)–30 (3)	January ?: Japanese detection February 22: H-bomb February 27: 2 H-bombs March 11: 2 explosions March 15: 32nd U.S. detection March 20–21–22: September 20–? October 2 (2 explosions): October 5–10–12–15–18–19–20–22–25–26 November 1–3 Very heavy fall-out reported from everywhere	Christmas Island April 29: H-bomb 1000 kt? Christmas Island August 22: low yield (balloon) September 2–11: H-bombs September 23: (balloon)
	300 kt 30,000 kt	? 20,000 kt	10 kt 300 kt

	U.S.A.	*U.S.S.R.*	*U.K.*
1959	NO EXPLOSIONS DETECTED		

	U.S.A.	*U.S.S.R.*	*U.K.*	*France*
1960				February 13: first explosion Sahara (plutonium), 60 to 70 kt April 1: at Reggane, plutonium, under 20 kt December 27: Reggane, small Pu device, possibly prototype trigger for H-bomb
				70 kt

1961				April 13: a few kt
	Operation "Plowshare" (underground) 2 after September 15 October 10	June–July: ? (see footnote) September 1–4–5–6–10–11–12–13 (2)–14–15–17–18–20–22: 100 kt, 50 kt, 100 kt, 100 kt, 5000 kt, 100 kt, 5000 kt, 100 kt, 100 kt, 5000 kt, 1000 kt, 100 kt, 1000 kt, 1000 kt, 1000 kt October 2–4–6–8–12–20–23 (2)–25: 1000 kt, 5000 kt, 8000 kt, 50 kt, 100 kt, 5000 kt, 20 kt, (underwater) and 30,000 kt, 1000 kt		

In June–July 1961 several reports were carried in Japanese newspapers to the effect that seismic equipment had picked up shock waves from the Soviet Union which were of non-geological origin. Simultaneously there came a U.S. report that an explosion had taken place "east of the Urals." Somewhat later, the Soviet Union said a gigantic blasting operation, using several thousand tons of explosive, had been carried out.

The resumption of the nuclear tests by the U.S.S.R. and the U.S.A. in September 1961, and the continuance of those started by France, are the inevitable outcome of a situation dating back to 1942. The armaments race makes it imperative to improve ceaselessly the fantastic arsenal which has already been built up. The bombs of 100 megatons announced by the U.S.S.R. are each capable of destroying life in an area of about 15,000 square miles (by their heat effects), and are the logical sequence in the military sense of the earlier devices. The technology of rockets makes it imperative to place such super-bombs in fairly small warheads, which necessitates many further tests.

13

Radioactive Fall-out

"FALL-OUT" is a perfectly descriptive term. Its meaning has been considerably extended during the past few years, and now covers a whole group of substances which come down to the ground and originate in many ways. Fall-out can be divided into three types [40].

Immediate Fall-out. This is the microscopic debris, or large-grained dust, blown up to an altitude of several miles. The time of descent is a few minutes to several hours. The spread is from a few miles to several hundred miles down-wind.

Tropospheric Fall-out. This involves very fine dusts thrown up to an altitude of about 7 miles, to the limit of the troposphere. These particles are driven by the winds around the earth, and the time of descent is several months.

Stratospheric Fall-out. This is specially due to fission-fusion and fission-fusion-fission bombs. It consists of dusts blown to heights of 30 miles and extending laterally in the huge mush-room cloud. It includes the vaporized fragments of bomb casings and of the unused portions of the charges in the form of indivi-dual atoms and molecules. Time of descent is spread over years, and in the stratosphere there is a layer of radioactive dust which surrounds the earth like a gigantic belt where the vestiges of all the H-bombs exploded in the past few years are mixed.

TYPES OF FALL-OUT

The most important contribution to the study of radioactive fall-out from bombs is obviously that which concerns world contamination. We will now analyse fall-out from A- and H-bombs, its physical, chemical, and radioactive characteristics, as well as the time of descent.

It is fundamental to know also, as precisely as possible, the

distribution around the world of fall-out from explosions, and this will be done in Chapter 15.

For this, two distinct cases must be examined:

1. that of low- and medium-yield A-bombs;
2. that of the super-bombs: H-bombs and fission-fusion-fission bombs.

The standard Hiroshima/Nagasaki bomb sets free an energy of 20 kilotons—that is $8{\cdot}3 \times 10^{20}$ ergs, or 23,000,000 kilowatt-hours. The mushroom cloud rises to the tropopause, which is the upper part of the troposphere about 9 miles above the surface of the earth. Bombs of higher power drive their clouds to higher levels still, of about 12 miles.

H-bombs of one megaton and more have clouds of very different shape with an axis reaching great altitudes of 25 miles and more, and with lateral extensions of several hundred miles above the tropopause.

This gives rise to three types of fall-out.

The radioactive dusts from A-bomb clouds, broken up and diluted by winds, fall back to the ground according to atmospheric vagaries—rain, wind, snow. Most of the coarse dusts fall in the immediate neighbourhood of the explosion and in the few hundred miles covered by the cloud under the action of the prevailing wind. A proportion of fine dust at higher altitude is carried on by high-altitude wind and is spread around most of the atmosphere in a rapid cycle.

Thus, European countries detected the passage of the clouds between four and seven days after explosions in Nevada. The distance covered was about 6000 miles. A few years ago the Japanese laboratories detected the second passage of the dusts from Nevada explosions, after a complete circle round the world. Some dust came directly over the Pacific, but some also travelled eastwards over Europe, the U.S.S.R., and Central Asia.

It is obvious that radioactive decay, on the one hand, and the movements of the atmosphere, on the other, fairly rapidly disperse detectable traces of fall-out from individual A-bombs. Nevertheless, they travel around the world, and although fall-out may be partially diluted, uniform atmospheric diffusion in both hemispheres is not certain.

Fall-out occurs at random but along the tracks of the pre-

vailing winds. Therefore, some countries must receive far more than others. Heavy rainfall can bring down high activity still suspended in the atmosphere a long time after an explosion and 6000 to 12,000 miles from where the bomb was exploded.

Fall-out from H-bombs follows a widely differing pattern. The amounts of dust and other matter vaporized by the very high heat yield is far, far greater than in the first case. Fall-out around the test site is thus also much more abundant. This was the cause of the accident to the Japanese fishermen on the *Fukuryu Maru* in the morning of March 1, 1954. The boat was covered, a few hours after the explosion, with a rain of ash as intensely radioactive as radium (one curie per gramme, that is 37,000,000,000 disintegrations per second per gramme of ash). And the vessel was 94 miles away. At the same time, 82 natives on the Rongelap and Ailingnae islands at a distance of 87 miles were also affected.[1]

Apart from this direct fall-out, which takes place in a few hours following a test, and which can spread to more than 600 miles downwind of an explosion, a fine radioactive fall-out similar to that of the A-bombs must be described. This matter pollutes the troposphere and travels round the earth in exactly the same way, taking from three to four weeks.

Finally there is the very slow fall-out from the stratosphere taking several years.

Now we have summarized the whole fall-out question we will go into details of the fall-out mechanism without analysing the radioactive content of the dust clouds. These consist, as we have said, of soil dusts torn from the surface where a bomb has exploded at ground-level. This is due partly to blast effects and partly to vaporization of the soil by the nuclear heat. To this must be added the vaporized remains of the bomb mechanism and residual nuclear explosive. Last, and not least, are the fission products formed when the charge is made up of heavy elements, together with the isotopes formed by neutron activation.

Dust Dispersal

The rate of descent of the dust depends on the calibre of the particles thrown high into the atmosphere. A body left free in

1. They received doses estimated at 175 röntgens and 60 röntgens respectively. *Medical Survey of Marshallese two years after Exposure to Fallout Radiation.* BNL 412 (T-80) Brookhaven National Laboratory.

space is subject to gravity. But opposing forces come into play when the particle is small; air viscosity slows down the rate of fall, and for extremely small particles there is no more fall but a state of equilibrium where the dust floats under the action of wind and is brought down only by rain or snow, which sweep the air of these foreign bodies.

The rate of fall of dusts in function of their size is well known. The following table gives the time of descent from 7½ miles (12 kilometres) and up, related to the diameter of the particles expressed in microns (one micron = 1/1000 millimetre), and supposing the particles are of sand (silica):

Diameter in microns	*Time of Fall*
840	0·37 hour
250	0·7 hour
160	2 hours
75	8 hours
33	40 hours
16	7 days
8	28 days
5	2½ months
2	4 years

The speeds of descent in centimetres per second are indicated below:

Diameter	*Speed in cm/sec*
1 mm	393
200 microns (0·2 mm)	78
100 microns	26
20 microns	1·3
10 microns	0·3
2 microns	0·01

Supposing the central mushroom cloud of an H-bomb rises to 15½ miles and spreads laterally about 60 miles, it is possible to trace a map of the spread of fall-out for particles of a diameter of 0·2 millimetres ([41], p. 87).

The distribution area of particles of 0·1 millimetre diameter is even greater and this has been proved by the fact that on this fateful March 1, 28 Americans on the island of Rongerik, 125 miles from ground zero, and 157 natives from the island of Uterik, 280 miles away, were contaminated by fall-out.

The fall-out area for dusts of 0·1 millimetre diameter in function of the prevailing winds is given in Fig. 11 for three of the thermonuclear explosions of the March/May series at Bikini ([41], p. 89).

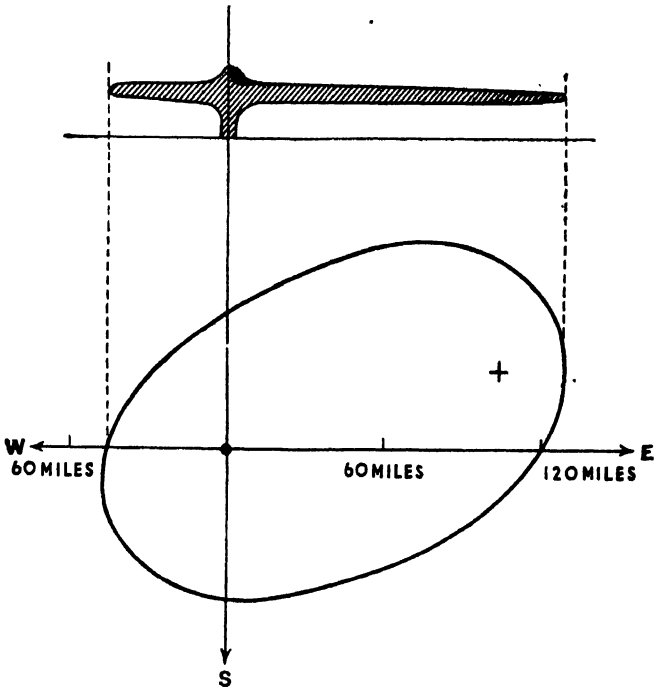


FIG. 10. FALL-OUT AREA FOR ASH OF 0·2 MILLIMETRE DIAMETER FOR THE "BRAVO" TEST OF MARCH 1, 1954.

The location of the *Fukuryu Maru* is marked by a +

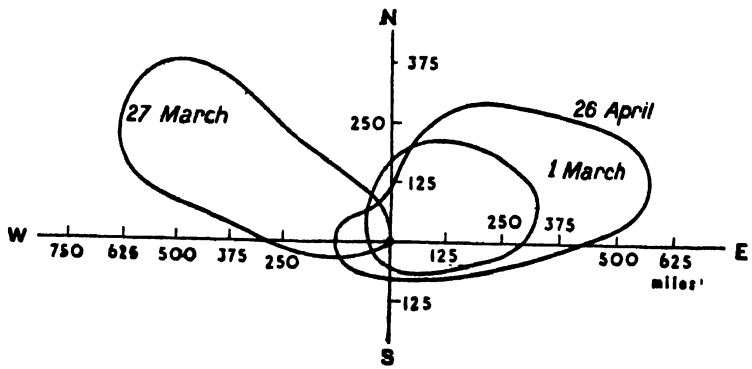


FIG. 11. AREAS COVERED BY FALL-OUT OF 0·1 MILLIMETRE DIAMETER DUSTS AFTER THE BIKINI EXPLOSIONS ON MARCH 1, 27, AND APRIL 26, 1954

It is apposite to note that a greater explosive energy for a bomb does not necessarily imply a greater dispersion of fall-out. The energy of the atmospheric oscillations following several explosions has been calculated by Japanese observers as follows ([41], p. 91):

	1/11/52	1/3/54	27/3/54	7/4/54	26/4/54	5/5/54	*Impact of the Siberian meteorite in 1907*
Energy of atmospheric oscillation in millions of kWh	140	38	15	?	9	39	8·8

This very interesting table was the only scientific attempt to measure the energies of thermonuclear tests. It shows us that the explosion of November 1, 1952 ("Mike") was of fantastic energy, compared with the 15,000-kiloton "Bravo." It would appear to have been three times as powerful as the latter.

In spite of these energies, the weakest explosion, that of April 26, seems to have resulted in the greatest spread of radioactive dust, both in area and in distance. The test of March 27 must have taken place in a strong easterly wind.

Although it is not easy to determine the amount of radioactivity dispersed by the cloud, it is possible to glean some precious details from known facts concerning the standard A-bombs. The "Trinity" trial of July 16, 1945, the first, gave the following data:

The bomb was at the summit of a 98-foot-high tower. The fireball reached the ground since its maximum radius was 460 feet and the amounts of dust sucked up were very large. The fission products were mixed intimately with this dust and returned to the ground as fall-out in varying areas. The table gives the proportions of fission products of varying particle sizes, which fell to the ground within given times:

	Proportion fall-out (per cent.)	*Diameters of particles (in microns)*
0 to 22 minutes	3·8	840
22 to 42 minutes	12·6	840/250
42 minutes to 2 hours	14·5	250/150
2 to 8 hours	18·1	150/75

But the finer dusts, below 70 microns, remained in suspension much longer and took with them 51 per cent. of the activity,

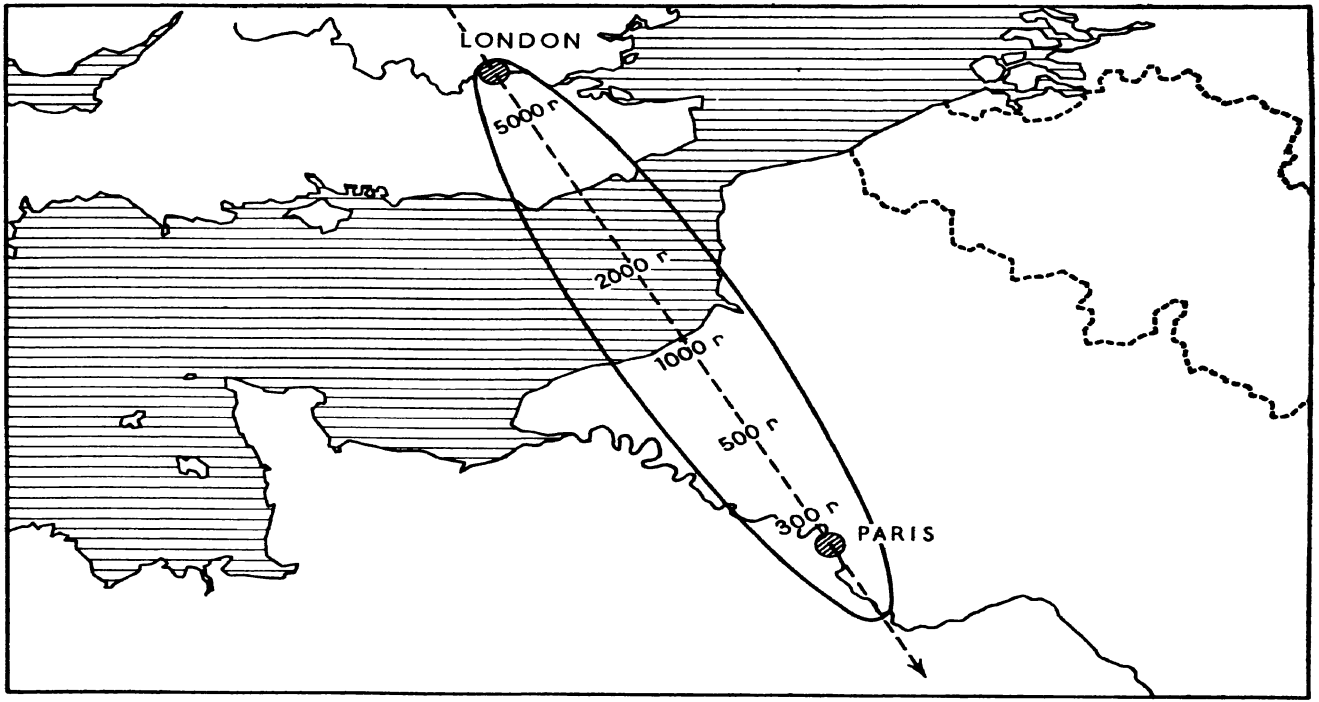


FIG. 12. FALL-OUT AREA OF RADIOACTIVE DUST WHICH WOULD RESULT FROM A 15-MEGATON H-BOMB (Bikini, March 1, 1954) DROPPED ON LONDON, IF A 22 M.P.H. WIND WERE BLOWING TOWARDS PARIS

Radiation doses after 36 hours of exposure, in röntgens, are given for the oval zone

which was thus spread far afield. Experience of this phenomenon was soon forthcoming, since, after this "Trinity" explosion, radioactive dust fell first on cattle 15½ miles away from the explosion but in the same State of New Mexico. These animals lost their hair in patches in a few weeks, and these became blister-like lesions. Later, the lost hair—originally reddish—grew again but was grey and white.

The most remarkable effect of that dust was in the State of Indiana, 1250 miles from Alamogordo. And it made its presence felt in a curious way. High-sensitivity photographic plates made in an Indiana plant were found to have fogged areas after developing. The cause was traced back to radioactivity in the cardboard packing. The cardboard was made partly from straw harvested in the vast area drained by the Wabash River whose water is used in many irrigation schemes. The waters of this river had been fed by rain polluted by the radioactive remains of "Trinity."

The sequence of events was remarkably rapid since in this case the contamination was discovered on August 6, 1945—that is, 20 days after the event.

Application to Europe

An official American release on H-bombs [42] published on February 15, 1955, gives a more accurate idea of the danger of fall-out from H-bombs with uranium tampers. The analysis is made for a 15-megaton bomb (type "Bravo," March 1, 1954).

The fireball would have a diameter of 4·4 miles and destruction would be total over a diameter of 10·6 miles. London or Paris would be wiped off the map. Severe damage would occur in a band 5–6 miles deep around the central desolation and lighter damage in a further 11 mile belt. If the London–Paris wind were blowing at a speed of 22 m.p.h., the radioactive fall-out would be dispersed by the wind and be deposited in an ellipsoidal region indicated by Fig. 12.[1]

At 170 miles fall-out would begin eight hours after the explosion and last for several hours. The extremity of the fall-out area would be 250 miles from the centre of the explosion. If London were the target of such a bomb, Paris could, with the right wind conditions, receive a rain of radioactive ash such that

1. All this data concerns a ground-level explosion.

a human being exposed to it for 36 hours would get 300 röntgens of external irradiation. This would cause the death of 15 per cent. of the population exposed (800,000 inhabitants of Paris and its outer suburbs). The regions covered by the ellipse between London and Paris would, of course, receive doses higher than 300 röntgens, reaching and exceeding the 600-röntgen level, which is mortal for a human being in a short time.[2]

Other fall-out patterns are possible, and that given by the Japanese report on the explosion of March 27, 1954, reached a total elongation of 600 miles, while that of April 26, 1954, stretched over 800 miles. This would mean, under the same supposed conditions as above, that French territory would be crossed completely from north to south by a band of radiation covering two-thirds of the country.

These few figures show to what extent a conflict with H-bombs involving Europe should be inconceivable.

2. The total area of this ellipse is about 7,700 square miles. In round figures, the area of the United Kingdom is 94,300 square miles, that of France 212,800 square miles, that of Belgium 11,800 square miles, and of Switzerland 15,900 square miles.

14

Detection and Measurement of Fall-out

How can fall-out be measured and followed; what methods can be used to detect its presence [40, 43, 44]?

Several methods have been used, and one of them has been adopted by the services of the U.S. Atomic Energy Commission.

First, there is direct air-sampling by a powerful pump which forces thousands of litres of air through a filter. The latter stops the dusts and is afterwards analysed, either by testing with a counter, or by calcination followed by radioactivity measurements on the ash.

When sampling is done by aircraft, no pump is needed, the forward speed being enough to force sufficient quantities of air into the sampling filters to collect adequate amounts of dust.

An Example of Direct Detection

Radioactive decay initially permitted observers to date explosions with some accuracy. This was the basis of some very interesting work carried out in India several years ago. In a published account [45], the following points are noteworthy.

No rain fell on Calcutta in March or at the beginning of April 1954, and air samples taken on the roof of the Institute for Nuclear Physics gave no traces of abnormal radioactivity. However, at the end of that month, on the 29th, very heavy doses of activity were found in the monsoon rains and this continued, with the rains, till mid-July—the March to May 1954 American test series included six thermonuclear shots.

Most of the activity was beta and thus came from fission products, while the gamma level was not much higher than the normal due to cosmic radiation.

A very different picture was derived from high altitude sampling of dust. The Indian physicists took advantage of the curious

property displayed by oils and greases of fixing large amounts of radioactive isotopes. They measured the activities of the oils and greases in the engines of airliners in service at the time on the run Calcutta–Guahati and return, Calcutta–Djakarta return, Calcutta–Singapore, and Calcutta–Rangoon [45].

The table below indicates clearly the haphazard diffusion of radioactive dust, varying considerably according to the altitude and the date of the flight. Activity is indicated in number of disintegrations per minute and per gramme of oil. Background of 20 counts per minute has, of course, been subtracted from the figures.

April 1954	*Flight*	*Altitude (feet)*	*Activity (counts per minute per gramme)*
8	Guahati and return	8,200	Nil
9	Guahati and return	9,800	58 ± 8
10	Guahati and return	8,200	38 ± 2
11	Djakarta and return	12,100	121 ± 5
12	Guahati and return	8,200	108 ± 13
13	Guahati and return	8,900	25 ± 5
14	Guahati and return	8,900	6 ± 4
15	Guahati and return	8,200	Nil
16	Guahati and return	8,900	10 ± 5
18	Singapore	12,100	73 ± 4
19	Guahati and return	9,800	19 ± 4
20	Guahati and return	9,800	12 ± 7
22	Guahati and return	9,800	19 ± 3
22	Rangoon	9,800	6 ± 1

The notation $\pm$ indicates the margin of experimental error and 58 ± 8 means that the counter registers an average of 58 disintegrations per minute but that the statistical fluctuations are 8 so that the real measure of activity lies between $58-8=50$ and $58+8=66$.

The table shows an increase in activity between April 8 and 12 corresponding to the H-bomb of April 7, with subsequent fluctuations.

The analysis of the rain samples is even more significant. The next table gives the number of counts per minute per litre of rain collected. The last column gives the proportion between this and normal. All samples were measured a few days after collection to eliminate parasitic radioactivity due to the presence of naturally occurring radon from the soil.

There was a sudden rise from May 15, which would appear to correspond with the explosion of May 5, also recorded in Japan. But the analysis of radioactive decay gave the Indians a supple-

mentary source of information. They returned by extrapolation to the origin of the activity, which was followed for one month in their laboratories. The date found in this way was between May 10 and 12. However, they pointed out that nothing in their work could indicate the source of the fission products, and that these could quite well come from an explosion in Siberia which took place a few days after the end of the American series in the Pacific.

Rains of	*Counts/min/litre*	*Proportion to Normal*
April 29	240±20	2·5
May 15	320±50	9
May 20	1560±35	7
May 22	1450±46	7
June 1	200±13	2·5
June 4	1043±60	2·8
July 5	Very low	1·2

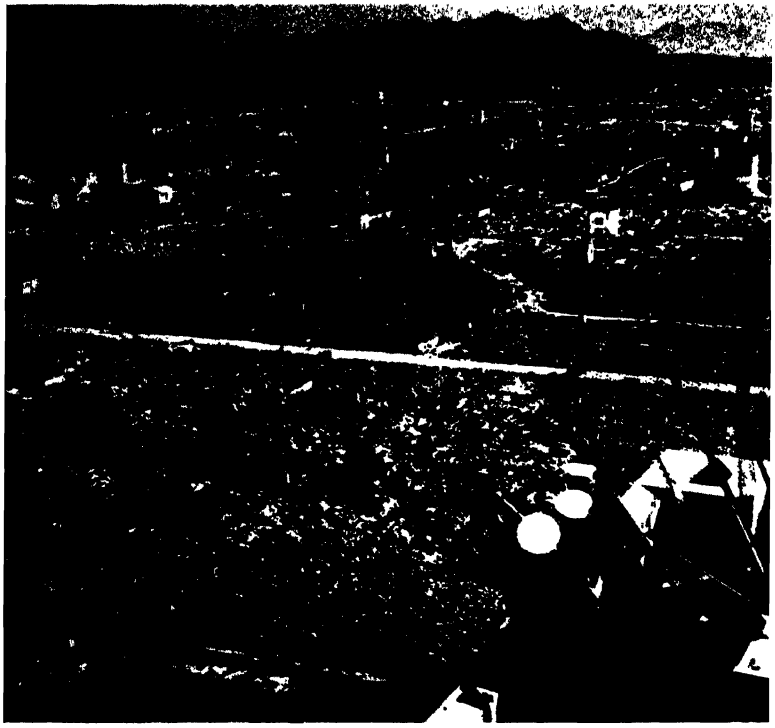
Although chemical analysis of the elements in these fine dusts is not possible due to the small amounts present, the radioactive decay of the mixture makes it possible to detect by physical methods the existence in it of substances with varying half-lives —4·5 days, 10 days, 15 days, and 30 days. The isotope corresponding to this last figure must be cerium-141 of which large amounts are formed among the fission products (5 per cent.) and which is very abundant in the ash from composite bombs with uranium tampers.

The contamination of the high atmosphere by fine dusts held in suspension over long periods is also revealed by balloons. These are currently being used up to altitudes of some 20 miles for meteorology and for the study of cosmic radiation. The plastic bodies of these balloons pick up certain amounts of radioactive dust, and this is easily detected by counters following their descent after several hours or several days as the case may be. Many such observations have been made in Britain and also in the polar regions and in Greenland.

Photographic Plate Method

Another method employed in the early stages between 1946 and 1950 was that based on photographic plates. The ionizing particles emitted by radioactive isotopes leave an imprint on photographic plates. For example, an electron betrays its passage through the emulsion of a plate by a fine and irregular

Smoke from the Nagasaki bomb billowing 20,000 ft above the



A view from the highest building in Hiroshima showing the devastation caused by the 20-kt bomb dropped on the city. Buildings made of reinforced concrete generally remained standing, but were gutted by fire.

The great heat from th Hiroshima bomb affecte the paint on a gas-holde $1\frac{1}{4}$ *miles from the centre o the explosion. Where thi wheel and spindle shielde the paint from the heat, 'shadow' was formed.*

track which can be observed through a microscope after developing the emulsion. Similarly a high-energy atomic particle leaves a straight track, and an atomic nucleus which explodes under the impact of a cosmic particle is revealed by the tracks of electrified particles which are emitted in all directions. A large proportion of observations in modern nuclear physics is carried out by using photographic plates with special emulsions.

That films can be fogged by penetrating radiation is well known. There have been a number of Press reports over the past few years that whole batches of photographic plates had been spoiled, either because their packing had been radioactive, or because active dusts had got into the manufacturing plant. The latter has been reported in Europe: residual activity is thus strong enough to ruin products manufactured thousands of miles from the explosion site. Big photographic plants have to use air-conditioning and filtering to prevent the ingress of radioactive particles. Similarly they must keep a very close check on all their raw materials, such as the animal products used to make gelatine.

This is becoming more and more difficult because atmosphere and biosphere are now uniformly contaminated.

This blackening of photographic plates has a famous precedent which happened in the summer of 1949 during which the U.S. specialists learned that the U.S.S.R. had exploded an A-bomb, although in 1946 it had been forecast that Russia would need ten years to build the weapon. A plane specially equipped to study cosmic radiation was on a routine flight—consisting of following a fixed course at a predetermined altitude—to collect on photographic plates traces of secondary cosmic radiation. On return to base the plates were developed. They were almost jet black—saturated by ionization. The plane had flown through a dispersing cloud of radioactive debris from a Siberian explosion which was travelling over the U.S.A. a few days after the event.

Planes equipped with collecting tubes were sent up along the same trajectory as the first, and again found the highly active cloud. Analyses proved that there was no doubt the U.S.S.R. had exploded a fission bomb of high energy.

Of course, all this took place at a time when A-bomb effects could be followed individually. Radioactive decay ensured the almost complete disappearance of high-activity dust in one or two

months. Since then, however, the H-bomb has completely changed these analyses, since a layer of radioactive dust now extends from the high stratosphere to ground-level with a very slow rate of descent.

Dust Collection on Adhesive Film

The simplest and most effective method of collecting active dusts and particles is that using adhesive film. This is the solution adopted for the air monitoring stations of the United States Atomic Energy Commission. Some of these were installed in 1948 on American soil. Experience gained with the method demonstrated its usefulness, and they were extended in 1952 to sites outside U.S. territory. Completed in 1954, a widespread network of 88 stations is observing the slow descent of fall-out.

The collectors are horizontal squares of a film of plastic material, cellulose acetate, covered with a coating of a substance which is adhesive when damp. They are fixed in place each day at 1 yard from the ground and at 2 yards from one another, so that they can easily be replaced if damaged. The gum catches not only the dry dust but also that in the raindrops. Each day, at a fixed time, the films are removed and sent by plane to a central laboratory of the A.E.C. in New York, where their activity is measured.

Other and better recipients have been studied, the best being boxes with high sides. These collect much more dust, but are almost impossible to handle for long-distance dispatch to New York. The personnel of the stations cannot be highly qualified and, moreover, the dust collectors must be light and easy to send by plane. Some 21 months of studies showed that gummed film was 63 per cent. effective compared with the high-sided boxes or pots, so that an accurate figure for daily fall-out could be obtained by multiplying results based on the analysis of adhesive film by a factor of 1·6.

Measurements are carried out by calcinating the film at 600°C and passing the ash through a beta detector. This is done on average three weeks after the films have been exposed to the air. This has the advantage of eliminating practically every trace of radon (half-life between three and four days).

On the other hand, some short-lived fall-out isotopes are lost, and the measurements do not correspond to an integrated dose

of all the activities of the fission products. This defect became important in the case of measurements made on fall-out over the United States after the Nevada trials.

At this point it must be stressed that this sampling of fall-out dust has a wider significance than a simple series of measurements. It is the result of a decision to determine world-wide contamination, especially by the slow stratospheric fall-out from the H-bombs, and above all by strontium-90.

Technical discussions have been held on the effectiveness of gummed film. It appears that the method is very suitable for dry dust but less for rain and still less for snow—and rain and snow bring down large proportions of the suspended matter. Some stations use heaters to melt the snow on the films. This widespread procedure would appear to result in the loss of far from negligible amounts of activity.

Again, study of wind movements shows that atmospheric transportation of these dusts takes place horizontally just as well as vertically. The films are spread horizontally, and would fix little or none of the dust moving parallel with the ground.

Further studies have shown that in the case of radioactivity brought down by rain two forms are present: that of dusts suspended in the droplets, and that of matter which has gone into solution. In this connection there is a surprising statistical fact—namely, that only three of every hundred raindrops are radioactive.

The network of American stations includes 26 in the United States and 62 spread around the world. Maps giving the sites and details of the measurements carried out by them have been published.

15

World Contamination

TESTS by filtering of air in devices carried by planes flying at 50,000 feet and samples taken by balloons sent up to 100,000 feet have in both cases demonstrated the presence of strontium-90, and therefore of fission products piled up by thermonuclear explosions since 1952. All the earth's atmosphere is thus affected by the presence of long half-life isotopes.

These traces of explosions have a very slow and probably regular rate of descent. Let us presume that a composite bomb creates 400 kilogrammes. Strontium-90 content would be 3 per cent., say 12 kilogrammes. Half this amount comes down in the few hours after the explosion with the coarse dusts. The six remaining kilogrammes are thrown high into the stratosphere. After three years, three of these will have been deposited, after a further three $1\frac{1}{2}$ kilogrammes, three years later $\frac{3}{4}$ kilogramme, and so on.

But the half-life of strontium-90 is 28 years, and in the above conditions its decay is negligible. After 6 years $10\frac{1}{2}$ kilogrammes of the original 12 will have reached the ground, and at the end of that period they will still contain 9·3 kilogrammes of strontium-90 and 1·2 of its radioactive decay products. The same argument applies *a fortiori* to caesium-137 since its half-life is 33 years.

Thus it is anticipated that from the date of suspension of H-bomb testing, some 20 years must pass before contamination of the ground with radioisotopes ceases.

The distribution of radioisotopes in the atmosphere or the stratosphere obeys laws which are still incompletely understood. The movements of these remains of nuclear explosions depend on many seasonal factors as well as the latitudes where they took place and their force. To find out dwelling-time in the atmosphere or time of descent, and the substances in immediate and

long-term fall-out, the evolution of fission products must be followed from the moment of the explosion until their contact with the earth.

It appears easy, *a priori*, to carry out this study by concentrating on the isotopes in fall-out; these are the materials which must be observed, it should be sufficient to measure their radioactivity. But this reasoning, which was valid before 1952 when the nuclear explosions were spaced out and of relatively low yield, no longer held true after the thermonuclear bomb trials. These created a permanent reservoir of free dusts and isotopes in suspension in the lower and upper atmosphere. It has thus become very difficult to distinguish in any fall-out sample between matter from a recent explosion and matter which has been in suspension for a long time as a result of earlier experiments.

In consequence a tracer method was used to mark a nuclear explosion with easily detectable radioisotopes of sufficiently long half-life to be detected for some length of time and followed in their journeys round the earth.

This experiment took place during the summer 1958 series of explosions carried out by the United States [46]. To a few atom bombs of medium energy was added a quantity of tungsten (element number 74), which is a mixture of five stable isotopes, including tungsten-184, which amounts to 30·6 per cent. of the total. These isotopes, in the flux of fast fission neutrons, capture a few of them and form radioactive isotopes through the (*n*, gamma) reaction. The 184 isotope gives 185, with a half-life of 74 days—a 0·43 MeV beta emitter. There is also tungsten-181, which has a useful half-life of 145 days. But the stable 180 isotope from which it is produced by neutron capture exists only to the extent of 0·135 per cent. in tungsten. In these conditions *only* tungsten-185 is useful as an atmospheric tracer.

In the high-power bombs a longer-lived isotope was incorporated to serve as a stratospheric tracer, since the period of suspension is much longer. Rhodium, element number 45, was added to the H-bombs. This element has only one stable isotope, Rh-103. It is the (*n*, 2*n*) reaction which produces Rh-102 with a half-life of 210 days, emitter of electrons, positrons, and gamma radiation. The very intense flux of thermonuclear neutrons, also of high energies, enables this reaction to proceed with a considerable yield. This confirms similar reactions observed in the

debris of thermonuclear explosions by the Japanese in 1954 (uranium-237 produced in great abundance by (n, $2n$) reactions on the uranium-238 of the bomb's shell).

First Results of Tungsten-185 Marking

A scientific study [47] gives some results of the detection of tungsten-185. Dated April 30, 1959, one year after the tungsten had been injected into the atmosphere, it was carried out in May, June, and July 1958. The bombs tagged with tungsten were exploded at the beginning of the American "Hardtack I" series in the Pacific which began on April 28, 1958. The American A.E.C. indicated only 14 trials between April 28 and July 26 [48] but later data show a greater number (see table in Chapter 12).

A short article in *Pravda* on June 6, 1958, signed by Dr V. Bogorov, assistant director of the Institute of Oceanography of the Academy of Science of the U.S.S.R., reported that the Soviet research vessel *Vitiaz* was cruising 1875 miles west of the Marshall Islands to measure the radioactivity of rainfall in the framework of International Geophysical Year studies. On May 23, 1958, he said, measurements on rainwater showed increasing amounts of activity, and by May 29 it was 100 times normal. "So much so," the article went on, "that work had to be suspended and the ship sailed out of the active zone. Prophylactic measures were taken on board, moreover."

This clearly indicated that some of the May explosions employed fission devices. Furthermore, on May 29, Britain had detonated a bomb near Christmas Island in the Pacific.

The measurements of May, June, and July were of great importance in tracking the spread of fission products with which the tungsten-185 was mixed. For this purpose, the report said, 18 air-filtering stations had been set up along the meridian 80° west from Coral Harbour in Canada to Punta Arenas in Chile. The basic measurement was of the beta activity per hundred cubic metres of filtered air for each sample (see Fig. 13, p. 169).

Dispersion was very rapid, since by May tungsten-185 had been detected by ten stations from Columbia (South Carolina, U.S.A.) 40°N to Antofagasta (Chile), 23·5°S. At the end of June it had reached Moonsonee (Ontario, Canada), 51°N and Punta Arenas (Chile), 53·5°S. By July it had got to Coral Harbour (Canada), 64°N. The heaviest concentrations appeared first at the high-

altitude stations, such as Chacaltaya (Bolivia), 17,132 feet; Huancayo (Peru), 11,004 feet; Quito (Ecuador), 9250 feet; and Bogota (Colombia), 8664 feet. The speed of dissemination to both hemispheres must be noted and, especially, the transfer from north to south. The graphs showed that the amount of activity which passed over to the Southern Hemisphere was greater than that which spread out in a ribbon around the intermediate latitudes of the Northern Hemisphere. There was a maximum at the equator and two other maxima each side at 40°N and 40°S. The dispersion spread to all parts of the world, following bands which spread laterally, very fast at first and then more slowly beyond the 50° latitudes.

One important feature of these experiments was that *inter alia* they demonstrated how much the atmosphere had been contaminated by fission products since 1952. It is evident that all air sampling takes in not only the fission products from recent explosions, as shown above, but also all those of earlier explosions which are still suspended in the atmosphere. Tungsten-185 tracer tests have demonstrated [47] that the *relative* pollution by this isotope was much more marked in the Southern Hemisphere because of the smaller amounts of fission products present there. The Northern Hemisphere is so contaminated that the proportion of tungsten-185 to fission products in June 1958 was 1 per cent. to 2 per cent. in Washington, 5 per cent. in Miami (Florida, U.S.A.), 30 per cent. at Miraflores (Panama Canal); but at Quito (Ecuador) 70 per cent., and at Lima (Peru), nearly 100 per cent.

These tests were made along the meridian 80° west at about 7800 miles from the explosion area. Three other stations were also equipped to make the tungsten-185 recordings—at Subic Bay (Philippines), at Pearl Harbour, and on the slopes of the 11,139-foot volcano, Mauna Loa (both Hawaii). The Subic Bay post recorded large quantities of fission products and tungsten right from the beginning of May, which confirms the report from the Soviet oceanographic vessel *Vitiaz* which was at the time on a course between the Marshall Islands trial area and the Philippines. However, after the end of the month a sharp drop in activity was noted. On the other hand, no tungsten-185 was detected in Hawaii during May, and it was not until June that Mauna Loa and Pearl Harbour began recording fall-out of this isotope, the former receiving ten times as much as the latter.

This again demonstrated that the higher atmosphere was polluted first and that fall-out descent to earth was gradual. Disparity between the high-altitude and sea-level stations was accentuated in July.

This series of recordings made by 21 specially equipped posts is of capital importance. It demonstrated quite conclusively that worldwide distribution of radioactive debris in the form of fall-out was a reality and provided a convenient yard-stick to measure it. Instead of seeking the evidence of this distribution in the presence in the soil of fission products, it became possible directly to follow the tracks of fission-product clouds from the moment of their birth in an explosion until the moment of contact with the ground.

This tracer method is of very high sensitivity. The quantity of tungsten-185 formed by these explosions almost certainly did not exceed 100 grammes. Nevertheless, the presence of this isotope can be detected anywhere in the world at a rate of one disintegration—recognizable by its 0·43 MeV beta particle—per minute and per 100 cubic yards of air filtered.

The report also allows the inference to be made that more than one tungsten-marked explosion took place and that the last in the series contained far larger amounts of fission products and much less tungsten. One fact should be correlated with the foregoing: that the 90 to 100 megatons of fission-based explosions up to 1958 created some 5000 kilogrammes of fission products, at least half of which were injected into the earth's atmosphere.[1] If, therefore, it is possible to detect anywhere in the world the presence of radioactive atoms coming from an initial dispersion of a hundred grammes or so at a single point, there is nothing surprising in the fact that fission products are found everywhere, as the following section relates, since they were dispersed in large amounts from about 20 points on the earth's surface.

Strontium-90 and Caesium-137 in Soil

U.S.A.—CANADA—HAWAII—SWEDEN

Apart from the question of fission products in plant metabolism, which will be examined in detail in the next chapter, direct measurement of radioactivity in soil has been carried out.

1. See Chapter 9.

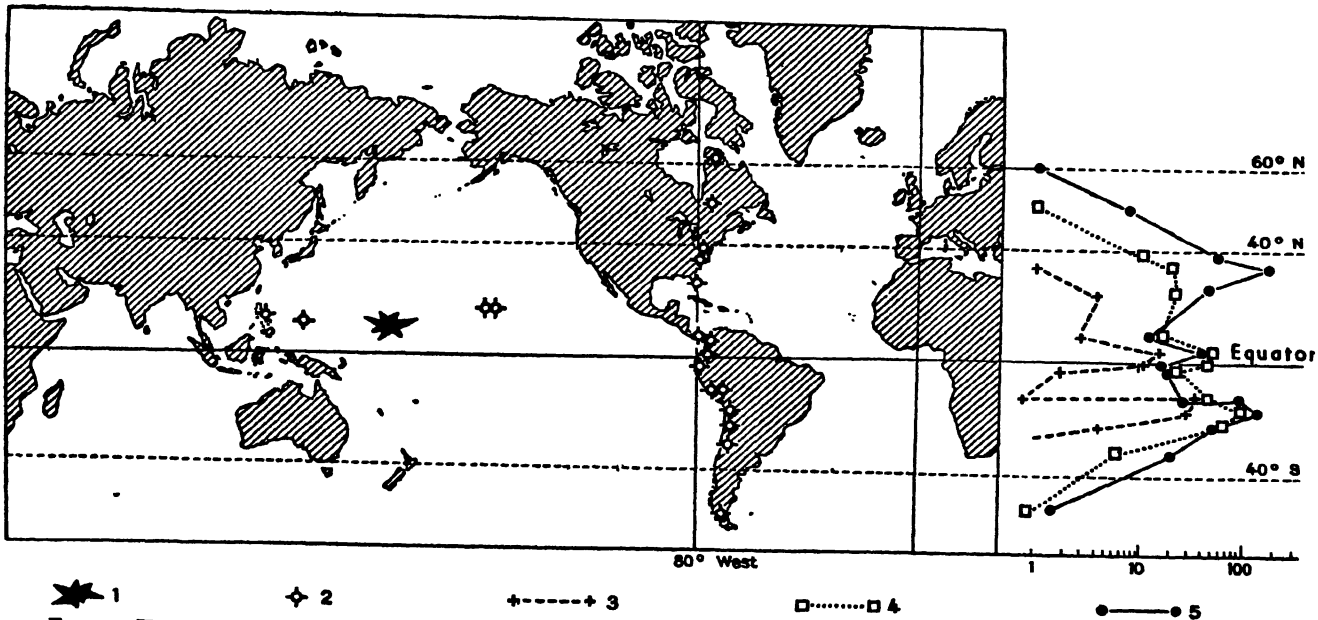


FIG. 13. THE DISTRIBUTION OF THE RADIOACTIVITY OF TUNGSTEN-185 (MAY, JUNE, AND JULY, 1958) FROM EXPLOSIONS IN THE CENTRAL PACIFIC.

Measurements were carried out by stations along the meridian 80° west.

1. Area of explosions marked with radioactive tungsten (May 1958). 2. Detection stations. 3. May 1958 measurements. 4. June 1958 measurements. 5. July 1958 measurements

Number of disintegrations of tungsten-185 per minute and per 100 cubic metres of air filtered on the meridian 80° west.

A brief analysis of work [49] on soil contamination, carried out from 1956 to 1958, follows. The researcher's aim was to find out whether measurements simply based on the gamma activity of caesium-137 were sufficient to permit calculation of the quantity of strontium-90 present. This is because assay of strontium-90 requires rather difficult and delicate chemical manipulations. Its beta radiation is also not very easy to measure. On the other hand, the gamma emission from caesium is very easy to detect. Since the two isotopes are always found together and if it could be shown that their proportions did not vary (we shall see in the next chapter that they sometimes do) too widely, a simple measurement with a scintillation counter would give the caesium content, whereupon a simple numerical relation could be used to deduce the quantity of strontium-90 present.

Determination of the proportion between caesium and strontium activity in air was carried out on twelve samples taken all over the world in 1957 and was found to be $2{\cdot}10 \pm 0{\cdot}31$. The same operation was performed for rainwater from January 1956 to June 1958 from sixteen sites around the world, and the proportion was calculated as $1{\cdot}54 \pm 0{\cdot}22$ (bases of these measurements are in the study quoted).

Determination of soil burdens consisted in the analysis of gamma radiation by scintillometer, using nine samples for which strontium-90 content had already been measured by chemical means. The table follows.

Depth (cm)	*Place and date*	*Cs-137 (micromicrocuries per kg of soil)*	*Sr-90 (micromicrocuries per kg of soil)*
	Ithaca (New York)		
0/5	Oct. 1956	188	101
0/5	Oct. 1957	377	167
5/30	Oct. 1957	25	31
	Ottawa (Canada)		
0/30	April 1957	63	46
0/30	April 1958	81	54
	Kawailoa (Hawaii)		
0/5	Dec. 1957	411	219
5/30	Dec. 1957	36	23
	Leilehua (Hawaii)		
0/5	Dec. 1957	226	171
5/30	Dec. 1957	48	24

(To make this table more readable for laymen, decimals have been cut out as well as the margin of error, which did not exceed 10 per cent.)

The average figure for the proportion between Cs-137 and Sr-90 activities is $1{\cdot}64 \pm 0{\cdot}34$. But there are variations which must reflect differences of the chemical behaviour according to soils and according to depth. Similarly, geographical areas exist where both for rain and for soil the proportion is lower than elsewhere, which tends to confirm the existence of some chemical action indicated by other work.

All this relates to direct fall-out—air, rain, soil. We know that there is an organic selection mechanism which discriminates between strontium (chemically similar to calcium) and caesium (chemically similar to potassium).

Results published in February 1959 by the Public Health Service of the U.S. Department of Health, Education, and Welfare of a series of tests show that for milk the proportion between Cs-137 and Sr-90 activities in milk from ten centres scattered throughout America varied from $6{\cdot}28 \pm 1{\cdot}28$ to $15{\cdot}45 \pm 5{\cdot}62$, the average being $10{\cdot}09 \pm 2{\cdot}27$. There is thus more caesium than strontium fixed in milk since the natural proportion of 1·6 becomes 10 in milk. Grass first and then the cattle act as chemical filters eliminating more strontium than caesium.

Significant too in the table on soil radioactivity are:

1. the increase to almost double between October 1956 and October 1957 in the soil content in New York State;
2. the extremely high content of the soil samples taken in Hawaii, nearer to the H-bomb test areas;
3. the ten times lower content (at least) of the deep layers of soil (5 cm to 30 cm) compared with the superficial layers (0 cm to 5 cm).

It is very interesting to compare the data relating to Hawaii, the U.S.A., and Canada with figures compiled by Swedish scientists [50].

The next table is similar to the preceding one in that it is expressed in micromicrocuries of Cs and Sr per kilogramme of soil, but layers sampled were 0 cm to 2·5 cm, 2·5 cm to 5 cm, and 5 cm to 10 cm deep. The four sources of samples taken during the summer of 1957 are given, together with annual rainfall and the nature of the soil. A comparison of this table with the preceding one is very instructive, and indicates quite clearly to what extent strontium and caesium affect the superficial layers

of the soil. The Americans took samples from one layer of soil 0 cm to 5 cm deep, while the Swedes divided this and made two separate analyses. In the first U.S. case a much lower average content is found than in the first Swedish case because this figure drops sharply after a soil depth of 2·5 cm. Furthermore, the Cs-137 content was not measured below 5 cm by the Swedish workers, who take it to be nil, whereas the U.S. results show that at depths between 5 cm and 30 cm quite considerable amounts are found.

Place and depth in cm	*Cs-137 (micromicrocuries per kg of soil)*	*Sr-90 (micromicrocuries per kg of soil)*
Skarhult, 22·4 in rainfall (moraine)		
0 to 2·5	1450	574
2·5 to 5	126	66
5 to 10	—	18
Fröslida, 46·5 in rainfall (fine sand)		
0 to 2·5	574	210
2·5 to 5	125	74
5 to 10	—	22
Ultuna, 20·9 inr ainfall (clay)		
0 to 2·5	447	216
2·5 to 5	0	47
5 to 10	—	16
Offer, 19·7 in rainfall (moraine mud)		
0 to 2·5	57	202
2·5 to 5	0	22
5 to 10	—	4·5

Fission Product Content of Soil

Another, more direct method determines the rate of fall-out and the superficial amounts of certain radioisotopes. These activities at present are measured in millicuries per square kilometre—total if all the gamma emission of all the fission products is considered or limited to the beta activity of strontium-90 or again to the gamma activity of caesium-137.

The following data are drawn from some recent tests carried out in several countries: Sweden, Britain, U.S.A., Czechoslovakia, the Soviet Union.

Strontium-90 in Sweden. From the report [50] come measurements of superficial quantities (depths from 0 cm to 20 cm) of Cs-137 and Sr-90 expressed in millicuries per square kilometre.

For the summer of 1957, the table is as follows:

	Cs-137 (*millicuries per square km*)	*Sr*-90 (*millicuries per square km*)
Skarhult	39·4	17·1
Fröslida	19·2	9·0
Ultuna	12·5	9·0
Offer	13·1	5·5

In Britain. A table [51] has been published giving the speed of deposition, per year, of strontium-90 in rainfall recorded at Milford Haven (Pembrokeshire).

Year	*Sr*-90 (*millicuries per square km*)
1952–54	2·0
1955	2·4
1956	2·5
1957	2·6
1958	5·4

This corresponds to an aggregate of about 15 millicuries per square kilometre at the end of 1958.

World Figures. A graph summarizing a number of measurements of Sr-90 content in the soil in various countries has been published [52]. This figure is a function of latitude, as demonstrated by the tungsten-185 tracer work described at the beginning of the chapter. Moreover, this graph covers a large number of *averages* on soils with widely varying calcium contents. It must also be remembered that fall-out is affected by rainfall and thus varies widely from country to country and indeed from one region of a country to another. The above table for Sweden underlines this fact and shows activities ranging from 17 to 5 for areas which, on a world scale, are very close to each other and which have roughly the same rainfall (22·4 inches at Skarhult and 19·7 inches at Offer).

The graph of world Sr-90 distribution at the end of 1958 is given only as a reference which shows the variation of average content with latitude (Fig. 14).

TOTAL ACTIVITY

Other measurements have been made on the gamma emission (and sometimes beta emission) of the whole gamut of fission products and other isotopes (such as zinc-65) in fall-out.

U.S.A. Gamma activity of the major fission product emitters in the soil was measured [53] in Illinois in May 1957:

Isotope	*Millicuries per square km*
Zr–95/Nb–95	69
Cs–137	13·5
Rh–106	67
Ru–103	67
Ce–144/Pr–144	92

This represents a total gamma activity of 308·5 millicuries per square kilometre.

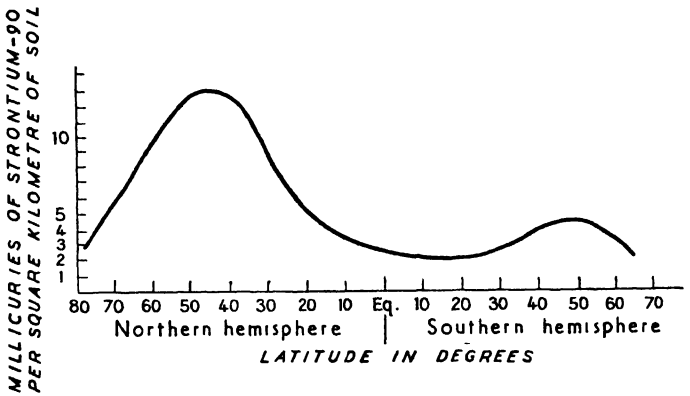


FIG. 14. SUPERFICIAL DOSES OF STRONTIUM-90 THROUGHOUT THE WORLD AT THE END OF 1958, SHOWN ACCORDING TO LATITUDE

Britain. Sampling carried out in 1959 covered various areas in Britain [51] and again demonstrated the existence of regional variations.

The gamma emitters are the same as those in the U.S. table plus cerium-141 and the doses are expressed in millicuries per square kilometre.

This example is by far the best that could be presented to demonstrate how fallacious a role averages can play in the vexed question of fall-out. On British soil alone, total gamma doses vary from 209 to 797, nearly four times as much. Counts in the column relative to caesium range from 13 to 133, ten times higher. If these last figures are compared with the Swedish data on caesium (table on p. 172) it will be seen how widely they differ. Moreover, the average of the two columns is 21 for Sweden and

52 for Britain, more than twice as much. Yet the graph of Fig. 14 certainly does not show such a doubling in activity between latitudes 50°N and 65°N.

	Ce–141 *Ce*–144	*Ru*–103 *Rh*–106	*Ce*–137	*Zr*–95 *Nb*–95	*Total*
	(*activities in millicuries per square kilometre*)				
Kew (Surrey)					
August 26, 1959	—	8	13	34	
Chilton (Berkshire)					
June 3, 1959	—	34	22	158	
Abingdon (Berkshire)					
June 25, 1959	24	22	28	135	209
Milford Haven (Pembrokeshire)					
July 14, 1959	17	18	43	182	260
August 28, 1959	19	27	54	130	230
Windermere (Westmoreland)					
July 10, 1959	24	33	75	331	463
Snowdon (Caernarvon)					
June 27, 1959	40	57	133	567	797

In consequence, only very large numbers of measurements carried out all over a country give an exact idea of the distribution of fall-out and an estimate of ingested doses can only be made in each particular case.

Czechoslovakia. Work carried out in Prague [54] gives details of analyses of fall-out made in 1958 and 1959 and indicates, *inter alia*, that activity was 175 millicuries per square kilometre from November 1, 1958 to January 30, 1959 and 152 for the three months that followed.

U.S.S.R. The cumulative activity of fall-out has been followed from January 1954 to January 1958 for the Leningrad area and the work has been published [55]. The graphs show that activity increased step-wise (after each series of trials), the number of explosions more than offsetting radioactive decay. From 10 millicuries per square kilometre at mid-1954, total activity rose to 70 at the turn of the year, then to 120 a few months later. It dropped to 80 and stayed around that figure until the beginning of 1957 and then climbed to 170 and then 200 by the end of that year.

16

Fission Products in Living Things

THE distribution of radioactive fall-out all around the globe causes universal contamination of all living things: micro-organisms, plants, animals, and human beings.

Every living thing constantly draws substances it needs for its structure and its energy from its surroundings. Humans breathe, eat plants and the flesh of animals, and drink liquids—water, milk, or spirits.[1] All the materials humans assimilate have themselves assimilated the atoms of which they are made. Basically, flesh is built up by the chemical transformation of the organic molecules synthesized by grass. The same reasoning applies to milk and to beverages made from plants, such as tea, coffee, and wine. From grass to human beings many molecular redistributions have taken place but, in the final analysis, the atoms which make up a human body come from the earth and the air. The following table gives the sixteen major elements in the human body in order of abundance. There are, of course, many more, since almost all elements, even radium, are present in any organism, mostly as minute traces. The table gives the mass of each of the sixteen in the body of a man weighing 70 kilogrammes [56]. The elements indispensable to life are constantly exchanged, and a human body is completely renewed several times during its life, more or less rapidly for the various organs. These exchanges are much slower for the bones and the nervous system, including the brain, than for the muscles, for example.

Thus, if radioactive isotopes become mixed with the elements of earth, soil, and water, the chemical elements to which they belong that are absorbed by organic substances will contain a certain proportion of these poisons. There will be no differentiation

1. A man absorbs about 500 kilogrammes of food and 500 litres of liquids per year. He breathes about 26 cubic yards of air per day.

between radioactive and inert iron since the chemical reactions involved are concerned not with the nucleus but only with the external layer of electrons. The radioactive elements artificially created and disseminated throughout each physical zone—soil, water, air—will be drawn into the metabolic cycle, assimilated, accumulated, and excreted, just like stable atoms of the same elements.

Element	*Weight in kg in a 70-kg body*	*Element*	*Weight in grammes in a 70-kg body*
Oxygen	45·5	Sodium	100
Carbon	12·6	Chlorine	100
Hydrogen	7	Iron	3
Nitrogen	2·1	Magnesium	3
Calcium	1	Zinc	2
Phosphorus	0·700	Manganese	0·2
Potassium	0·245	Copper	0·15
Sulphur	0·175	Iodine	0·03

Strontium is chemically like calcium, and can be ingested in its stead. Similarly, caesium can be ingested instead of potassium. But calcium and potassium are abundant in the body. We take up about one gramme of calcium daily in our food (milk, vegetables), and a fraction of a gramme of potassium (meat, cereals). Strontium-90 and caesium-137 will be present in these foods in certain proportions due to biological selection, and there will be a build-up of strontium-90 in bone, and of caesium-137 in muscles, until a quasi-permanent equilibrium level is reached. 'Quasi-permanent,' because pollution will last a long time as a result of the long half-lives of these two isotopes.

This chapter is devoted to the detection, in the organic world, of the most dangerous fission products. There is no question about the results of tests in this field carried out since 1956. They have also been made in great numbers the world over. The examples have been chosen to cover a wide selection from plants to human beings and present a full picture of world conditions. The following will be dealt with:

1. The presence of fission products in plants—Sweden.
2. Fission products in deers' antlers—Britain.
3. Strontium-90 in foods (vegetables, milk, cereals)—U.S.A.
4. Caesium-137 and strontium-90 in powdered milk and in fodder—Britain.
5. Caesium-137 in powdered milk and in soils—Sweden.

6. Strontium-90 in powdered milk, vegetables, and in the bones of humans and of sheep—Australia.
7. Strontium-90 in human bone—world.
8. Iodine-131 in human thyroids.
9. Fission products in human lungs.

Radioactivity in Plants in Sweden

A piece of research work of very great value was carried out by Dr Pontus Ljunggren of the Lund Geological Institute (Sweden) [57]. The analysis is as follows:

Geological prospecting work on radioactive minerals has been in progress in Sweden for some years, and areas of high activity have been closely examined. During this work samples of various types of plants were examined to determine whether a "biogeochemical" method would give good results. It is known that plants can accumulate considerable quantities of certain elements if the soil is rich in them. It has often been possible to detect the presence of mineral deposits by analysing plants growing above them.

In carrying out this work it was noticed that the ashes of many plants had radioactivity levels much higher than those of the soils in which they were growing. This observation gave the impetus for a thorough examination of the activities of plants from several districts selected to give variations in soils and underlying rocks as well as topography (such as seaside, valleys, and hills). Nine widely different varieties of plants were selected for analysis.

The plants were first reduced to ash and the activity of the resulting product measured first by Geiger counter and then by scintillometer. But it was the beta radiation result that was finally selected as a working basis, as the gamma value varied enormously according to soils—as had been known for some considerable time.

Preliminary results showed that ashes of plants from the same region had, on an average, the same beta count. However, certain species accumulated larger amounts of radioisotopes than others. Moreover, the different parts of the plants gave different counts, the maximum being in the needles (conifers), the leaves, and the twigs, while the value for tree-trunks was the same as for the ground. In some cases the dead portions of the plants were

as active as the living parts. In others, on the contrary, the counts showed a considerable diminution in activity.

The table below gives the series of measurements of the radio-activity of ash obtained from pine needles coming from the great forests which cover the hills of southern and western Sweden. In the first column is the activity of the naked soil, and in the second the activity of the foliage of pines growing in this soil—activity being expressed in microröntgens per hour measured by Geiger counter in the period March–April 1959.

Activity of soil	*Activity of foliage*	*Activity of soil*	*Activity of foliage*
30	80	30	110
25	150	30	110
35	80	30	120
40	150	26	60
30	105	40	60
30	115	35	75
50	150	35	75
30	60		

These fifteen samples showed that the soils contained an almost stable amount of beta emitters (fission products), around 30 microröntgens per hour. On the other hand, pine twigs and needles varied widely, with maxima 100 per cent. higher than minima, and an average value of about 100 microröntgens per hour. This shows that there is here a biological accumulation.

The next table gives six identical measurements made on pines from the low-lying areas of the same regions in Sweden (March–April 1959).

Activity of soil	*Activity of foliage*	*Activity of soil*	*Activity of foliage*
25	50	30	85
25	45	35	55
30	60	35	90

The activity in the soil is slightly less than in the hills, probably because rainfall is less, and the counts for the pine needles are considerably lower than those from the hills, being about half as much, though still twice as high as for the soil (instead of three times as in the preceding case).

Later tests carried out by the Swedish Institute of Research for the National Defence demonstrated that gamma activity (the above measurements are of beta activity alone) was due to the long half-life fission products zirconium-95, niobium-95, ruthenium-103. They indicated that there was good reason to believe that yttrium-91 and strontium-89 were present in equal

quantity to the zirconium/niobium pair, and that caesium-137 and strontium-90 were present in quantities amounting to one-hundredth of those of Zr/Nb.

The amount of natural radioisotopes is negligible compared with these artificial activities due to fall-out products.

Samples taken from areas close to the coast are more radioactive than those of the lower hinterland. The same applies to samples from the foothills and the mountains. The lowest counts come from the low-lying country farthest away from the sea. It is thus clear that snow and rain are the vectors for a major part of the activity of the soil.

The author added that the beta activity of plants was generally between twice and six times that of the soil, and that some samples were up to sixteen times more active. He stressed the fact that concentration through living organisms is the most direct danger.

This is the essential fact which cannot be too strongly underlined.

The work was carried out in March–April 1959—that is, more than four months after trials had stopped. But some of the radioisotopes present have a relatively short half-life, for example that of cerium-141, which is only 32 days. At the end of four months the initial activity will have declined by half four times, so that it is only one-sixteenth of the original level (cerium accounting for 6 per cent. of fission products). Nevertheless, the Swedish results show that this isotope had already been drawn into the biological systems of the plants and was irradiating them with its beta and gamma activities.

This is the proof that short half-lives must not be neglected as was done initially, since it was supposed that the time of descent to earth was too long for the corresponding fall-out fractions to be significant.

Radioactivity in Antlers

Among the parts of an organism which need large amounts of calcium are, apart from bones and teeth, the horns of certain animals. In particular, the horns, or antlers, of red deer develop in a curious way which is not yet clearly understood. Studies have been carried out [58] in special centres to elucidate some of the mysteries of this bony development which starts at the bone of the skull. It is a seasonal phenomenon linked with hormonal functions. In the red deer only the male has these antlers, while

in reindeer and caribou both sexes are thus adorned. Work on the red deer at the Washington School of Medicine demonstrated that it was not only the sex hormones which had a predominant role in the development of the antlers, but also a factor of nervous origin since an asymmetrical hormonal change brought about a difference in the development in the antler on the opposite side. Tracer studies with radioactive calcium-35 revealed an extraordinarily high calcium content in the blood of the deer, but did not show why, suddenly each season, this calcium travelled to the antlers and was deposited there in large amounts.

But an important inference has to be drawn from the fact that one of the elements chemically very similar to calcium is strontium. Hence an analysis of antlers was made in Britain to measure the degree of accumulation of radio-elements of the same group as calcium resulting from bomb fall-out.

This was performed in 1958 [59]. The authors pointed out that biological concentration of radioactive isotopes brought to earth by fall-out is a continuous and growing problem closely linked with the production of all human food. They referred to the fact that measurements on strontium-90 levels had shown there was more in the bones of children than in those of adults because of the quick accretion of 'new' calcium during a child's skeletal growth. "The rapidity with which antlers are formed, linked with the fact that deer graze in mountainous areas known to receive larger amounts of fall-out, suggested that the antlers could be highly contaminated with radio-strontium."

The antlers of a red stag killed on November 3, 1957, on the island of Islay were tested for strontium. (Islay, west of Scotland, between England and Ireland, is indicated in Fig. 7, p. 69.) One of the antlers was reduced to ash, the strontium was extracted by chemical methods, and the activity was measured by Geiger counter. It was 126 Strontium Units (1 S.U. = 1 micro-microcurie of strontium per gramme of calcium present). It represented the activities of Sr-89 and Sr-90, possibly with traces of other elements of the same group and of heavy metals.

A transverse section two millimetres thick taken at a branching point of the other antler was placed on a special photographic film for a period of 82 days. The brilliant autoradiograph of the slice is perfectly clear in outline and shows that accretions take place around the periphery as could be expected, the 'fresh'

calcium increasing the diameter by external deposits. When part of the antler was separated into two zones (middle and periphery), chemical analyses showed that there was nine times as much activity in the periphery as at the centre.

The authors said they were able to obtain the antlers of a stag that had been killed in the same region in 1952. Analysis showed that in the intervening five-year period there had been a sharp rise in activity due to strontium, since the level in the older horn was 11·2 S.U. and exposure on a film for 92 days produced only a weak autoradiograph.

Such pictures—produced in special emulsions by objects containing radioisotopes—were obtained with other biological specimens, including the pre-molar of a sheep found dead on the slopes of Ben Lawers in Perthshire (Scotland) at an altitude of 1600 feet, and plants from the same region which had been suspected of containing large amounts of radio-strontium.

Such is the gist of this short, but very important, article. It is a pity that no measurements were made on the teeth of the sheep and especially the surrounding grasses. All we know is that strontium-90 content must have been very high since the autoradiograph was very clear. But nevertheless, the high level of pollution in the Highlands had been proved. And the high concentration capabilities of certain organs had been clearly demonstrated, with very high activity levels and a sharp increase by a factor of ten between 1952 and 1957.

Strontium-90 Content of Calcium-rich Foods, U.S.A. 1956–57

Regular determinations of the strontium content of certain vegetables, cereals, and milk rich in calcium have been made in the past few years. There follow the conclusions of analyses done at the end of 1957 [**60**] of produce of 1956 and 1957.

About one hundred samples were analysed—vegetables, cereals, liquid and dried milk, and drinking water from piped systems. Each sample of vegetables consisted of ten packets (three kilogrammes) of frozen produce, cereals were taken from ordinary shop packets and measured in samples of 200 grammes, while the liquid milk was from cows grazing on pasture which had not been ploughed. Meat, fish, and eggs were excluded because of their low calcium contents.

The experimenters sought to find out, *inter alia*, whether cooking removed any of the calcium (and of the strontium). The result was negative, and the water in which the vegetables were cooked according to ordinary culinary instructions had no more activity than tap-water.

The three tables cover:

1. vegetables taken from different areas in America, the period when they were picked, and their S.U. contents (micromicrocuries of strontium per gramme of calcium);
2. a similar table to the first, but for cereals;
3. milk, taking into account work by other specialists in 1956.

1. STRONTIUM IN VEGETABLES

Samples and dates		*S.U.*
MAINE		
Peas	Aug. 1956	21·3
WESTERN NEW YORK		
Green beans	Aug. 1956	20·2
	Sept. 1956	18·4
		8·6
Dry beans	July 1957	13·6
	Aug. 1957	11·3
Cauliflower	Oct. 1956	9·1
Maize	Sept. 1956	28·4
Spinach	June 1957	1·8
EASTERN PENNSYLVANIA, NEW JERSEY, LONG ISLAND		
Asparagus	June 1956	1·2
	May 1957	1·1
Green beans	Sept. 1956	8·0
	Dec. 1956	4·6
Lima beans	Sept. 1956	6·6
Cauliflower	End 1956	8·1
Peas	June 1957	10·0
Sweet Potatoes	1957	13·3
Potatoes	1957	6·1
Marrow	End 1956	11·5
WASHINGTON, IDAHO, OREGON		
Lima beans	Sept. 1955	6·3
Broccoli	Sept. 1956	3·7
Maize	Aug. 1957	2·1
Peas	June 1956	3·0
	July 1956	7·8
	June 1957	4·8
Potatoes	1957	8·7
Marrows	Sept. 1956	3·1
	Oct. 1956	3·7
EASTERN MARYLAND, DELAWARE		
Asparagus	Oct. 1956	1·7
Lima beans	1956	2·9
	Sept. 1956	8·4
Broccoli	Oct. 1956	4·7
		6·7
		8·5
Maize	Dec. 1956	3·6
Peas	Dec. 1956	1·3
TENNESSEE		
Okra	Aug. 1957	18·0
Spinach	April 1957	1·2
		6·1
Turnips	Feb. 1956	7·8
	May 1957	21·3
MINNESOTA		
Maize	Sept. 1956	1·6
Peas	June 1956	5·8
CALIFORNIA		
Asparagus	April 1957	1·8
Lima beans	Sept. 1955	10·0
	Sept. 1956	4·3
	May 1957	4·6
Broccoli	April 1957	4·0
Brussels Sprouts	Sept. 1956	4·3
	Oct. 1956	12·0
	Nov. 1956	1·1
	Dec. 1956	2·5
Cauliflower	Oct. 1956	28·5
	April 1957	22·5
Spinach	Mar. 1957	13·9
		9·1
		9·5

2. STRONTIUM IN CEREALS

Samples and dates		*S.U.*	*Samples and dates*		*S.U.*
U.S. CEREALS			U.S. CEREALS		
Wheat (New York)	1956	22·8	Flour (Illinois)	July 1956	6·7
Wheat (Washington)	1955/56	9·1	Rice (unknown)	1956	4·0
Bran (Michigan)	Summer 1957	8·6	Wheat (unknown)	1956	37·5
			Oatmeal (unknown)	1956	5·7

3. STRONTIUM IN MILK

Samples and dates		*S.U.*	*Samples and dates*		*S.U.*
New York City	1956/57	5·6	Mississippi (State College) (powder)	1956	6·5
New York State (Perry)	1956/57	4·5	Missouri (St Louis) (powder)	1956/57	6·5
Mohawk Valley	Sept./Oct. 1957	6·6[1]	Oregon (Portland) (powder)	1956/57	7·0
North Carolina	Aug. 1957	5·3[1]	Wisconsin (Columbus) (powder)		5·5
Virginia (Rockingham County)	Oct. 1957	3·8[1]	New Jersey (Bergen County)	Sept./Oct. 1957	3·0–7·7
North Dakota (powder)	1956/57	10·0	New Jersey	Oct. 1957	5·5[1]

1. Average

These are the figures. The report stresses the wide variations, by a factor of four, in samples from the same area, due probably to differences in the calcium content of the soil. There are also seasonal differences which sometimes reach a factor of two from one month to the next.

Despite these wide variations, the authors have calculated averages: 6 S.U. for milk, 15 S.U. for cereals, and 10 S.U. for vegetables. Since the Americans take 85 per cent. of their calcium from milk, 4 per cent. from cereals, and 5 per cent. from vegetables, this means that in the period under discussion they were absorbing an average of 6·5 strontium units per gramme of calcium in foods. The figure for vegetarians could well be double.

Analysis of drinking-water in New York City showed that at the end of 1957 the content was 0·1 micromicrocurie of Sr-90 per litre. If a man absorbs one gramme of calcium daily from his food and a few litres of water, the food content will predominate.

The report ends with an estimate that an 'average' content of 6·5 S.U. entails a retention level of 1·6 S.U. It says that if the content remained constant (it rose) the level of 1·6 S.U. in the

bones would probably be correct for young children, half that figure for new-born babies, and between one-third and one-fifth for adults because of the slow replacement of the calcium fixed in the mature skeleton.

Caesium-137 and Strontium-90 in Powdered Milk and Fodder in Britain

A very detailed study of the presence of the long half-life (33 years) fission product caesium-137 in milk was carried out in Britain [**61**]. Major points and conclusions are as follows.

The study observes that the presence of traces of Cs-137 in human beings was the subject of a report in 1956 [**62**]. This had also been observed in Britain at the time. The major source of Cs-137, born in nuclear explosions and spread around the world with other fall-out isotopes, was probably cow's milk. The new study published details of Cs-137 and potassium content of dried milk samples collected at nine points in the United Kingdom, between April 1957 and June 1958. Samples of dried milk from one area had been under regular analysis since 1955.

Determination of Cs-137 can be done directly by electronic counting methods, since Cs-137 has a daughter-product, barium-137, which is an excited state and emits a gamma photon of 0·662 MeV. Moreover, potassium contains a natural radio-isotope, K-40, of very long half-life, which emits 1·46 MeV gamma.

The samples of powdered milk were generally of 2 kilogrammes with some of 500 grammes.

The Cs-137 content expressed in Caesium Units (1 C.U. = one micromicrocurie of caesium per gramme of potassium) was measured in this way for nine areas in the U.K.

For the Frome (Somerset) area, records run from March 1955 to July 1958. The powdered milk analysed was from skimmed milk. Starting at 9 C.U. in March 1955, the level rose suddenly to 27 in May, thereafter remaining steady for a year to rise to 35 in June 1956. There was then a period of fluctuation around 28 and then 30 from May 1957, and a sharp increase to 50 after the Windscale accident (October 1957, see Chapter 10). In December 1957 there was a decline to 25, but then a new increase in May 1958 to 50. After July 1958 the level began to drop again.

The graphs concerning eight other areas: Garstang (N.

Lancashire); Driffield (East Riding); Buckingham; Congleton (Cheshire/Staffordshire); Carmarthen; Carlisle (Cumberland/Dumfriesshire); Mauchline (Ayrshire); Coleraine (Tyrone, Londonderry) cover only the period from the beginning of 1957 until mid-1958. They follow the same trends as that for Frome with a higher peak for Garstang (45 miles from Windscale) during the accident (140 against 50) and for Carmarthen (100). On the other hand, some areas show no peak for Windscale and have a lower average.

The authors note that there is a seasonal decline in activity during the winter when the cows do not graze and are given dry fodder, but an increase in spring when they are put out to pasture. There is clearly a correlation between activity and rainfall, since the higher the latter, the more caesium there is in the milk. This has also been proved in the U.S.A.

The Windscale incident (analysed on pp. 107–112) brought to light another fact; that it is much more through superficial deposition on grasses that radioactivity is taken up into animal metabolism than through radioactivity present in plants by absorption from the soil by their roots.

The report also gave a significant comparative table of the caesium and strontium contents of fodder and milk. This makes for a better understanding of the mechanisms whereby these isotopes are taken up, first by plants and then by animals.

For Cs-137 the figures were (C.U.):

	Fodder	*Milk*	*Proportion*
Carlisle	32	35	1·1
Carmarthen	99	61	0·6
Driffield	26	30	1·2
Frome	43	38	0·9

For Sr-90 (S.U.):

	Fodder	*Milk*	*Proportion*
Carlisle	57	4·8	0·08
Carmarthen	100	7·5	0·08
Driffield	44	4·6	0·10
Frome	80	5·5	0·07

Germane to these tables is the fact that fodder contains 9 to 18 grammes of potassium and 4·5 to 6·5 grammes of calcium per kilogramme.

These two tables demonstrate that caesium and strontium follow different routes in living organisms. Practically all the

caesium content of the potassium is assimilated. But in the case of strontium the cow acts as a living filter, since only 8 per cent. of the strontium ends up in the milk by comparison with the amounts fixed in the fodder.

Human body-burden of Cs-137 in Oxfordshire and Berkshire in the second half of 1957 averaged 45 C.U. This was of the same order as the concentrations in fodder and milk from the same area.

This piece of research demonstrated the complete correlation between the quantity of caesium-137 in plants, in milk, and in humans. It showed the seasonal variations due to the fact that the composition of the cows' food varied according to the time of the year: in winter the amount in the milk declined because the bulk of the food was hay, harvested in summer when rains were infrequent. The quantity of Cs-137 was directly proportional to rainfall.

Radioactive contamination of grass and milk was greater in the first five months of 1959 than ever before, according to the annual report for that year of the Scientific Adviser to the London County Council. The reason was an increased admixture of air from Arctic regions which had been contaminated by nuclear tests in the previous autumn. Radioactive dust from this source was deposited by rain. The amount of airborne fission products decreased rapidly in the second half of 1959. Strontium-90 content in food also decreased, but more slowly, because of the amounts held in the soil.

A report by the Agricultural Research Council of the U.K. [63] shows that for 1958 and 1959 the twelve-month mean values of Sr-90 content in milk revealed a marked increase of about 40 per cent. in the first half of 1959. Thereafter values remained relatively constant. The report adds that though levels of Sr-90 in milk resulting from the injection of this isotope into the stratosphere *should* decline, the rapidity and extent of the decrease cannot yet be predicted. It is perhaps appropriate to point out that the summer of 1958 was very wet and that of 1959 remarkably dry.

Another section of the report [63] surveying British flour supplies indicates that for samples taken during 1959 bran from flour of Russian origin contained 537 S.U. against 10 for Australia, 59 for North America, and 133–225 S.U. for the U.K.

Caesium-137 and Strontium-90 in Powdered Milk in Sweden

Work on powdered milk in Sweden [50] yielded the following table.

Milk	*Date*	*C.U.*	*S.U.*
Whole	Aug. 28, 1947	1·0	0·14
	Nov. 29, 1955	17·0	2·50
Skimmed	Feb. 14, 1956	12·1	1·70
Whole	Apr. 24, 1956	12·2	4·98
	Oct. 22, 1956	28·3	4·32
	Jan. 6, 1957	17·0	3·37
Skimmed	June 1, 1957	18·8	4·54
Whole	June 21, 1957	22·1	3·37
Skimmed	Sept. 15, 1957	53·1	6·37
Whole	Dec. 13, 1957	22·4	4·88
Skimmed	Jan. 21, 1958	22·6	4·47

The figures recorded for the Sr-90 and Cs-137 counts confirm British experience, although the Swedish averages are for the most part considerably lower, due certainly to the lower rainfall in that country.

In general, and for corresponding seasons, Sr-90 content in milk is slightly higher in the U.S.A. than in Europe. This is due to short-range fall-out which contaminated American territory to a greater degree because of the Nevada test explosions.

Strontium-90 in Australia

Deposition of fall-out takes place in both hemispheres, although nine-tenths of the trials have been in the Northern Hemisphere. Australian researchers [64] have analysed dried milk, cabbages, sheep bones, and human bones for Sr-90 content.

The essential points are as follows.

The powdered whole milk was taken from points between 30 miles and 90 miles from each of the five state capitals. The strontium unit figures were:

	August 1957	*March 1958*	*August 1958*
Perth	2·9	1·8	4·9
Adelaide	4·2	3·8	7·7
Melbourne	4·0	2·7	4·4
Sydney	2·4	1·6	1·8
Brisbane	5·3	2·2	6·1

Here, again, there is a seasonal effect (drop in March compared with August) and regional variations according to the nature of the soil and local rainfall. However, in this particular

case there is no clear-cut correlation between rainfall and strontium levels.

In cabbage, the following doses were measured (in S.U.):

	August 1957	*August 1958*
Perth	4·0	4·0
Adelaide	2·3	4·3
Melbourne	2·1	9·4
Sydney	2·1	4·1
Brisbane	2·6	7·7

On the whole the figures recorded for these vegetables, as for the milk, are rather similar to those reported from other countries, although somewhat lower. Yet fall-out is much lower, as indicated by the graph of Sr-90 results according to latitudes (p. 174) and confirmed by actual measurements of Sr-90 per square kilometre, which gave 1·6 to 3·4 millicuries for the five capitals in August 1957 and 1·0 to 3·7 in August 1958.

Strontium-90 in Human Bone

Mixed with the calcium intake, the radioactive isotopes strontium-89 (51 days) and strontium-90 (28 years) penetrate the living body and are fixed mainly in growing bone and teeth. Milk has a high calcium content and thus it is the young who receive higher doses than adults because their bone structure is still growing.

All animal species are inevitably affected to different degrees. Sheep which graze on pastures directly impregnated with fall-out by rainwater will be more likely to assimilate large amounts. Humans, on the other hand, eat foodstuffs derived from plants and especially animals which have already 'filtered' a large part of the strontium through selection mechanisms. This is illustrated by measurements effected in Australia [**64**] on the Sr-90 content of bone from young sheep and from human beings.

For the sheep, the figures in S.U. were:

May–June 1957. 1·5 to 14 according to area, with an isolated recording of 21 for two sheep from a mountain district. Average 7·9.

August–September 1957. 1·0 to 12. Average 6·6.

August 1958. 1·5 to 16. Average 6·3.

For fresh human bone samples analysed between December 1957 and September 1958 in Australia, the table was as follows (in S.U.):

	Femur	*Vertebrae*	*Skull*	*Ribs*
Less than 24 months	0·54	0·57	0·85	—
24 to 59 months	1·00	0·61	0·90	—
5 to 20 years	0·34	0·31	0·35	0·30
Over 20 years	0·04	0·23	—	—

From work on human bone done in Britain comes the following table, again in S.U.[2]

	Mid and late 1958		*January–June 1959*	
	Minimum	*Maximum*	*Minimum*	*Maximum*
Stillbirths	0·3	1·4	0·6	2·5
0 to 5 years	0·3	2·9	0·4	6·9
5 to 20 years	0·4	1·3	0·3	2·7
Over 20 years	0·02	0·25	0·07	0·15

Measurements have been carried out on a worldwide scale [65], and the following tables have been established according to a mean for the whole skeleton, which contains about one kilogramme of calcium. The unequal contents of the various types of bone can be allowed for by applying the rough proportion that vertebrae contain 1·8 times more Sr-90 than the overall figure for the skeleton, the ribs contain the same dose as the overall figure for the skeleton, while the femur contains only half as much.

1. Content (S.U.) according to age group (adults) and over a period of three years:

	20–29	*30–39*	*40–49*	*50–59*	*60 and over*
1955/56	0·12	0·13	0·09	0·16	0·12
1956/57	0·13	0·15	0·12	0·15	0·12
1957/58	0·15	0·36	0·22	0·17	0·17

The increase is very marked over only three years up to the age of 50. Above this, the S.U. appear more stable.

2. For children and adolescents, continent by continent, in 1957–58:

	North America	*Europe*	*South America*	*Asia*	*Africa Australia*
Foetus	0·64	0·60	—	1·3	0·25
0–6 months	1·18	1·15	—	0·21	0·45
7–12 months	1·84	1·47	0·58	1·15	—
1–2 years	1·53	1·39	0·54	0·11	0·27
2–3 years	1·49	1·71	1·28	—	0·60
3–4 years	1·23	0·87	—	—	0·43
4–5 years	0·74	0·73	—	—	0·48
5–6 years	0·70	0·66	0·28	—	0·55
6–8 years	0·60	0·61	0·39	0·28	0·53
8–10 years	0·88	0·39	0·28	0·09	1·50
11–15 years	0·61	0·55	0·22	0·50	0·49
16–19 years	0·39	0·24	0·20	0·45	0·22

2. *Radioactive and Natural Strontium in Human Bone—U.K. Results for 1959. Part I.* H.M.S.O.

The S.U. values for North America and Europe can be reduced to a graph in function of age applicable to January 1958 (Fig. 15).

The value is high for unweaned children because of the large share of milk in their diet. It drops from 2 to 6 years, and then increases slightly from 6 to 12 because of the growth of the bone structure which demands a lot of calcium. This growth can be followed up to 22 years, after which the value remains stationary.

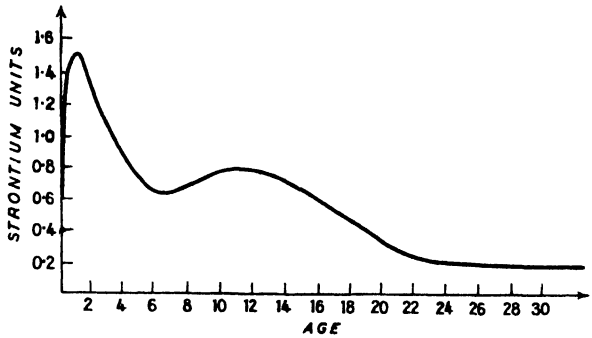


FIG. 15. AVERAGE STRONTIUM-90 CONTENT OF HUMAN BONE FOR NORTH AMERICANS AND EUROPEANS IN JANUARY, 1958

It must again be stressed that most of these tables and the graph (Fig. 15) represent mean values established from tens of measurements taken in hundreds of analyses. In reality, as the Australian table on sheep bone and the British table on human bone show, there are wide local variations. Human beings, because of the secondary or tertiary character of their food, will eliminate the very wide variations, but there will still exist fairly large differences.

RADIO-IODINE IN THE THYROID

To end this chapter, which aims to bring to light the radioactive pollution of living organisms by fall-out, it is interesting to give an example of penetration by a fission product, albeit one with a fairly short half-life. Iodine-131 has an eight-day half-life, which corresponds to the average biological half-life. The human thyroid weighs 25 to 30 grammes and contains 10 to 15 milligrammes of iodine; the blood plasma also contains iodine at a rate of 0·05 microgrammes per cubic centimetre. Iodine-131

has already been mentioned in the section dealing with the consequences of the Windscale accident (p. 111), and we know that it was found in the thyroids of adults and children on the day after the event. It is absorbed principally through respiration, since it is a vapour, and then through milk, since cattle absorb it from grass.

After nuclear tests a very clearly marked increase of radioactive iodine in the thyroid is observed because of this organ's considerable powers of accumulation of the element. This fact can even serve as a basis for detecting explosions because of its extreme sensitivity. And systematic measurements are being carried out on the thyroids of living creatures, such as sheep and cattle, throughout the world.

In man, doses [66] vary from 0·0008 millimicrocuries per gramme of thyroid to more than 0·01 or in proportions from 1 to 25 at the very least, in 1955 on the territory of the United States. The extreme cases [67] come close to 0·1 millimicrocuries.

In the zones near the explosion sites, tests [68] show doses four times as large as those due to iodine-131 during the 10 days which follow an explosion. This is due to the introduction via the respiratory tract of short half-life iodine isotopes:

I–132 (2·3 hours)	4·7 per cent. of fission products
I–133 (21 hours)	6·9 per cent. of fission products
I–135 (6·7 hours)	6·1 per cent. of fission products

Iodine-129 (0·9 per cent. of fission products) has a half-life of 17,000,000 years. It emits a beta of 0·15 MeV, and a gamma of 0·04 MeV, but its activity is weak because of this immense half-life.

Fission Products in Human Lungs (1959)

The mechanics of fall-out result in the presence of ions, dusts, and aerosols in the air breathed in. It is then certain that the lungs contain activity due to isotopes retained by the mucous membranes. Recent Austrian research on this subject has been published [69].

The direct analysis of gamma radiation in pulmonary tissue taken from three men who died in Vienna in April and May 1959, at 50–60 and 73 years, showed up the presence of the fission products Zr-95/Nb-95 and Ru-103. In the first subject, whose

lungs weighed 1370 grammes, there were 370 micromicrocuries of Zr-95/Nb-95 and 55 of Ru-103. For the two other subjects only one lung was analysed (600 and 400 grammes), and gave activities of 250 and 155 for Zr/Nb, and 45 and 25 for Ru, respectively. These values correspond to the activity in these isotopes of about 130 cubic yards of air at Vienna at the time of the measurements.

Analyses have also been made of sheep and cattle lungs and have given analogous results. These and those above can be summarized as:

> From 0·27 to 0·74 micromicrocuries of Zr/Nb per gramme of tissue, and from 0·04 to 0·14 of Ru-103 per gramme.

Determination by the authors of the caesium-137 content of liver and muscle in two subjects deceased at 60 and 73 showed 84 Caesium Units, much higher than the values found by measuring direct radiation from living subjects, which were 25 to 70 C.U. in 1956–57, and 30 to 60 at the beginning of 1958.

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Worldwide Distribution of Radioisotopes other than Fission Products

SINCE the radioactive pollution of the world finally forced itself into official awareness, fission products have been the subject of governmental concern, scientific investigation, and published works, almost to the exclusion of other radioisotopes.

The danger from fall-out because the radioisotopes it contains contaminate the atmosphere did not penetrate the minds of leaders of governments and organizations, of most scientists, and of the general public until 1955. Thereafter, some important work was carried out, but publication of reports and studies brought into being simultaneously—perhaps automatically—a quarrel between the specialists. Its subject was not so much the fact of radioactive contamination, but rather the effects that could be expected from it.

Among the most dangerous of the isotopes studied in this way is, without doubt, strontium-90, because of its long half-life and the fact that it is a 'bone-seeker'—that is, it becomes fixed in the skeletons of vertebrates. It was on this isotope that the great mass of reports was issued. Since strontium-90 became the 'star' of fall-out products, followed at some distance by caesium-137, there was a tendency to forget or minimize the fact that the fission products in fall-out are a mixture of numerous isotopes, *all* of which play individually an organic role. Their effects vary since they are absorbed to greater or lesser extents, have different radioactive and biological half-lives, and emit different types and intensities of radiation.

But, more important still, many other isotopes are born in a nuclear explosion, besides the fission products. Considerable amounts are formed by the action of neutrons on the bomb

housing, mechanism, and support, or on the surrounding soil, water, or air.

The aim of this chapter is to draw attention to the existence of these radioisotopes, some of which have a long half-life, and could play a not unimportant biological role if accumulated. There is some evidence to this effect.

The most important of these isotopes are:

1. Tritium
2. Carbon-14
3. Zinc-65
4. Manganese-54 and others
5. Cobalt-60
6. Plutonium-239
7. Other transuranic elements.

Particular attention will be paid to Zn-65 and Pu-239. Chemical effects will also be covered.

Tritium

This is the name of the hydrogen isotope having the mass number 3. Its nucleus, formed of one proton and two neutrons, is radioactive, with a half-life of 12 years, and is transformed into helium-3 by beta negative emission of a maximum energy of 0·02 MeV.

Fairly strong theoretical reasons indicate that tritium is used in thermonuclear weapons. This isotope is obtained by irradiating lithium in a reactor. Moreover, H-bombs must contain some lithium, and the same reactions occur during the explosion as in a reactor, so more tritium is produced. In this way, after each thermonuclear explosion, some of the initial charge of tritium, and all the tritium produced by the bomb reactions, is dispersed. There must thus be some radioactive super-heavy hydrogen in fall-out. Of course it is not detected directly in fall-out, but in compounds containing hydrogen, especially water. This means dilution such that the quantities present are infinitesimal, and it is a further demonstration of the value of tracer methods that they should have been able to detect so little activity against a continuously rising background.

Since 1954, tritium from the explosions has served as a tracer for the study of a large number of natural phenomena: rainfall, movement of subterranean waters, mixing of water in the seas, age of water in wells (in this way, certain wells have been found to contain water which had dwelt in subterranean layers for

more than 50 years), the age of the glaciers at the poles, and so on.

Measurements involving tritium can be expressed in tritium units. One T.U. is one atom of tritium for a million million million (10^{18}) atoms of hydrogen. Before the tests, tritium existed in nature and was continuously synthesized in the very high atmosphere by cosmic bombardment of the rarefied nuclei of nitrogen. Thus 'natural fall-out' fed the biosphere with this tritium, production of which was in equilibrium with radioactive decay. There must have been about 1·8 kilogrammes in the whole world, of which about 1 per cent. was in the air, a level of about 10,000 T.U.

Since 1952, the date of the first thermonuclear explosion, and especially since 1954, this level has not stopped rising, and there have been sharp increases in any rain that fell immediately after the explosions. For example, in Chicago, Ottawa, and in the water of the Mississippi [70] the level rose 2600 times after the Bikini series of March–May 1954.

During 1959 atmospheric abundance reached 500,000 T.U., fifty times the original level of 10,000. It appeared to be rising at a rate which would bring a doubling every eighteen months [71]. In connection with these numbers it must be remembered that natural hydrogen is very rare in the atmosphere, which explains the very high figures for the concentration of tritium. Before the advent of the H-bomb in 1952 there must have been about 200 grammes of tritium in the atmosphere. The above measurements enable the amount of tritium set free by thermonuclear explosions to be put at 10 kilogrammes at the very least. Little by little, this tritium entered into compounds formed with hydrogen—principally water—and the overall level rose albeit rather slowly because of its great dilution in water.

However, much higher concentrations were recorded in an important report [72] which gave the results of direct measurements of carbon-14 and tritium content of the stratosphere. This was done by analysis of samples obtained with high-altitude balloons.

On January 1, 1958, the quantity of tritium in the stratosphere alone, between 7½ miles and 22 miles altitude, was estimated at 14 kilogrammes ($2{\cdot}7 \times 10^{27}$ atoms). The total content of the troposphere (air up to 6 or 7½ miles altitude) is very difficult to

calculate, since tritium in suspension is quickly brought down by rain, while the stratosphere feeds the troposphere through the slow descent of the quantities in suspension. The total quantity of tritium formed since 1954 must then be estimated, and it is at least 30 kilogrammes.

Carbon-14

The importance of the artificial production of carbon-14 has been the subject of numerous publications since 1956 when a sharp increase in the amount present in the atmosphere predicted by theory in 1954 [73] was actually verified.

The biological role of this isotope is a result of:

1. its long half-life: 5600 years (see Fig. 3, p. 38);
2. its 0·15 MeV beta radiation;
3. the fact that it plays an essential part in all organic chemistry;
4. the fact that there is a continual exchange of carbon between the carbon dioxide and carbonates in air and water on the one hand, and the living organisms —plants and animals—on the other hand (the carbon cycle).

Carbon-14, providential gift to the archaeologists, exists in nature. It is produced in the high atmosphere by the action of slow neutrons on atmospheric nitrogen. These neutrons are formed by the disintegration of primary cosmic radiation.

This radiation does not appear to have varied for many thousands of years and has constantly created new carbon-14 so that an equilibrium with decay was reached long ago.

All living substances thus contain natural C-14. Wood and recent or fossil bones have measurable traces, so it is possible to determine the age of a sarcophagus, a piece of charcoal, or some remnant of a neolithic find by measuring their carbon-14 content. Each gramme of contemporary carbon will contain the same amount of carbon-14, decaying at a rate of 15 disintegrations per minute. In these conditions, a piece of organic material which has half this activity must be 5000 to 6000 years old, since the carbon-14 half-life is 5600 years. Radioactivity measurement methods could be used to determine the age of materials up to between 30,000 and 40,000 years.

However, since 1952 the atomic clock operating on C-14 has been seriously upset because thermonuclear explosions synthesize large quantities of radioactive carbon through neutron bombardment of atmospheric nitrogen.

The most recent experiments [71] show that 500 to 600 kilogrammes have been created by these explosions, whereas cosmic radiation produces only about 10 kilogrammes annually [74]. The atmosphere between 9 and 18 miles is impregnated with it, and fall-out is emptying this reservoir of C-14 at a rate which reduces the amount present by half every two to three years. This carbon-14 is taken up by rainwater, enters into carbon compounds, appears in the sea where it is absorbed by plankton, finds its way into plants through the carbon dioxide in the atmosphere, into animals via foodstuffs, water, and respiration. In this way the whole biosphere is becoming increasingly contaminated with C-14.

In the atmosphere the rate of increase [75] of C-14 in carbon dioxide was put at 3 to 5 per cent. between 1953 and 1957, and more since. The rate of increase will go up as the C-14 in fall-out passes into the carbon dioxide. Similarly all the carbon-bearing compounds of the biosphere will have a C-14 content increased by several per cent. when all the C-14 created between 1952 and 1958 has been assimilated. This will certainly take a long time, but how long is not known.

The overall increase for the Southern Hemisphere was given at 9·3 per cent. at the end of 1957 [76]. There is thus some discrepancy between analyses, which comes mainly from the fact that they were of different types of samples from different sites. On the other hand, the danger from C-14, in particular because of its genetic effects (as it must be present not only in the gonad tissue but in the gene-carrying chromosomes themselves) is a subject of controversy, and this is contributing to further complications in an already complex array of scientific facts.

The essential point to be remembered is that between 500 and 600 kilogrammes of C-14 have been artificially produced. An increase in the carbon-14 content of all living things over the next few centuries is absolutely unavoidable whatever the exact percentage may be: the extent of the biological and genetic effects will depend on the contamination level.

ZINC-65

Zinc-65 (element number 30) is a radioisotope of 246 days half-life. It decays to copper-65 (stable) by electron capture and emission of an 0·32 MeV positron in 1·5 per cent. of cases. About half the electron capture events result in an excited state of the resulting copper atom which produces gamma (1·12 MeV) and X-rays.

This isotope is not a fission product, and it was surprising to find large amounts of it in marine animals first, and then in foodstuffs.

Its detection was first reported in 1953 by Japanese workers who found it in fish [77]. Volume 13 of the papers presented at the first Geneva Conference mentions it twice [78, 79]. The study [79], in particular, stresses that Zn-65 accumulates in the liver and the stomach of fish, with a concentration factor of 10,000, according to earlier work (1953) on the subject, to which a reference has already been made.

Its presence has also been reported as a radioisotope diffusing around a nuclear site in the U.S. where it has been detected in the waters of the Columbia River which is used to cool the Hanford reactors and, subsequently, to irrigate farmland [23] (p. 97).

A still more recent study [80] recorded the contamination by Zn-65 of foodstuffs collected at random in the U.S.A. This material must have originated in nuclear explosions and was carried by fall-out clouds or by ocean currents.

Before analysing this work let us look at a possible source of the Zn-65 whose presence is difficult to account for. It could have been the thermonuclear explosions with their very high neutron fluxes which synthesized it from the zinc of protective buildings. It is known that several of the super-bombs of the 1954 and 1956 series in the Pacific were devices carried on barges (*Semi-Annual Report of the United States Atomic Energy Commission*, No. 24 (January–June, 1958), p. 394. A possibility is that some of these complex and heavy devices were protected by sheds with corrugated roofing. This would be enough to explain the formation of Zn-65 by (*n*, gamma) reactions from stable Zn-64, an isotope which forms 49 per cent. of natural zinc.

All this is hypothetical, and a major objection to this explanation is the fact that the U.S. scientists would have shown a

singular irresponsibility and lack of foresight by leaving kilogrammes of useless metal to receive a gigantic neutron flux. They had known what its effects would be since the "Mike" test explosion in November 1952.

The question of how this isotope is produced in explosions remains open. Unsolved, too, is its presence in the Columbia.

Zinc-65 in Pacific Fish—1954

The April–May 1954 explosions (Operation "Castle"—U.S.A.) in the Pacific initially contaminated the sea over a wide area of its surface. Currents swept the contamination far and wide, and it was also absorbed by plankton and by fish.

Japanese scientists, concerned at the disaster this represented for their country's fishing industry, caught and analysed many marine species, measuring the radioactivity in all the organs. This work constituted an important part of the collective study —of capital importance—entitled *Research in the Effects and Influences of the Nuclear Bomb Test Explosions*, published by the Japan Society for the Promotion of Science, Ueno, Tokyo, 1956. In particular, in volume II, pp. 839–860, there are three "Studies on the Radioactivity in Pelagic Fishes." The third [81] discusses the discovery of high concentrations of zinc-65 in the muscles of a skipjack (variety of tunny) caught by the vessel *Shunkotsu Maru* during a research trip in the South Pacific from April to July 1954. This isotope was also identified in an albacore caught by the same vessel. The authors have no doubt as to the identity of the isotope, although they cannot understand the absence of fission products with which this isotope should normally have been mixed. But an effect of biological concentration could have come into play if one supposes that the fish had fed on other marine creatures which had already concentrated heavy proportions of Zn-65. As indicated above, this factor can be as much as 10,000.

Zinc-65 in Food

This work [80], carried out in 1958 and at the beginning of 1959, and published in *Science* in November 1959, recorded the presence of Zn-65 in a wide variety of foods collected all over the United States but mainly in Cincinnati, Ohio, where the investigations were made. The authors collected their samples—

oysters, shellfish, meat, vegetables, eggs, milk, and fruit—reduced them to ash, and then carried out an analysis of the gamma emission with a scintillometer.

Of course they found the gamma from potassium-40, always present in living matter; the gamma from fission products such as Ru-106/Rh-106 and Zr-95/Nb-95, with a sharp peak at 1·12 MeV which is the gamma from Zn-65. The doses expressed in the following table are in micromicrocuries—that is, 2·2 disintegrations per minute.

Sample	*Date collected*	*Activity in Zn-65 (micromicrocuries per kg)*
Oysters	March 1958	124
	January 1959	178
Clams	May 1958	40
Meats (various)	September 1958	47
Leafy vegetables (washed)	August 1958	12
Root vegetables (washed)	August 1958	10
Eggs	August 1958	6
Fresh vegetables plus wheat (washed)	August 1958	4
Milk	August 1958	4
Fresh fruit (washed)	August 1958	3

The oysters came from Chesapeake Bay, Maryland, the clams from the east coast of the U.S.A. The mixture of meats consisted of equal weights of chicken, lamb, beef, and pork. Leaf vegetables consisted of equal parts of lettuce, cabbage, spinach, broccoli, celery, and cauliflower. Root vegetables included potatoes, sweet potatoes, carrots, radishes, beet, and turnips. The fresh vegetables mixed with wheat were unshelled peas and beans, and green beans. Fruit was apples, grapefruit, oranges, peaches, plums, melons, and strawberries.

The note 'washed' is very important because it is known to what extent pollution by fission products is superficial, brought mainly by rain. To exclude these sources of radiation and measure only internal activity it is important to wash all samples in running water before calcination.

The aim of this work was to show how widely Zn-65 is distributed and taken up biologically by plants and animals. There is a clear accumulation in marine species—clams and especially oysters. In the case of the latter, the graph of the gamma spectrum published in the work deserves special attention because it shows that these edible molluscs can retain in their flesh higher gamma activity from the fission products and the Zn-65 present

than from potassium-40, often quoted as the "major source of internal irradiation." If the coefficient 5 represents the gamma energy from K-40, then Zn-65 will produce 12, Zr-95/Nb-95 8, and Ru-106/Rh-106 18, while there will be between 10 and 15 for the gammas of energies between 0·1 and 0·2 MeV and more for lower energies not separated by the apparatus used.

All this does not mean that oysters and other shellfish have become unfit for human food. The authors point out at the end of their study that maximum doses observed in Zn-65 are one thirty-thousandth of the 'permissible' dose indicated in official recommendations [82], while those in vegetables and meats are 400,000 times lower than this level.

Moreover, these numbers should each be reduced by a factor of 100, because not all the ingested isotope will be fixed automatically in the sensitive organ. Zn-65 is also a bone-seeker, but the tables [82] show that only 1·5 per cent. of the ingested zinc will be fixed, and that the rest will be excreted.

This work does not constitute a 'biological warning' in the generally accepted meaning, but is a valuable indication of the existence of unsuspected and little-known contamination which must be studied more closely and watched.

Manganese-54

Produced in the same way as zinc-65, by neutron irradiation of natural manganese (Mn-55) and of iron (Fe-54), manganese-54 has a half-life of 290 days, and was discovered in the fall-out from explosions in the Pacific, in 1956 especially [83]. This isotope emits a characteristic gamma of 0·84 MeV.

The analyses in 1956 showed that the activity of this isotope was high, representing 40 per cent. of the total gamma from fall-out when the measurements were made. The amount formed initially was calculated at around 1,000,000 curies at least, which represents several grammes of Mn-54.

Manganese is an element found in all living organisms in trace amounts. It plays an important biological role, and certain types of plants and animals accumulate it in large quantities. The part played by manganese-54 in fall-out is, therefore, not negligible, and its presence must be attentively followed.

Other Isotopes produced from the Metals of Mechanisms and Casings

The discovery of Mn-54 in fall-out means inevitably that other long-lived isotopes must have been synthesized. Their existence, reported in 1954 [73], was discussed in a paper presented at the Monaco Conference [84].

Iron-55. With a half-life of 2·6 years, this isotope is formed in abundance by neutron capture in the nuclei of stable iron-54 (5·84 per cent. of the atoms in natural iron) and by $(n, 2n)$ reactions with iron-56 (91·68 per cent. of natural iron). This isotope decays to stable manganese-55 by the capture of one electron with emission of X-radiation as a result of rearrangement of internal electrons.

Iron-59. This has a half-life of 45 days and emits three negative betas of 0·27, 0·46, and 1·56 MeV, maximum energy, and three gammas of 0·20, 1·10, and 1·29 MeV.

Not so far detected, there must be some iron-60 of very long half-life—300,000 years. Its nuclei give birth to excited nuclei of cobalt-60 with a 10-minute half-life, after which they become ordinary radio-cobalt-60 with a half-life of 5·2 years which we will discuss later. The very long half-life of Fe-60 makes its activity very weak, and it could be detected only through the five gammas of cobalt-60. However, this isotope is formed directly in large amounts.

Nickel-63. Traces of this element may also be formed, resulting, as for Fe-60, from multiple neutron captures by stable iron isotopes according to the chain discovered by analysis of the ash from the first thermonuclear explosion in 1952 ("Mike"). Ni-63 has a half-life of about 100 years. It emits only one beta negative of 0·06 MeV maximum and no gamma.

So far as biological and metabolic accumulation is concerned, the presence of these long-lived radioisotopes of iron is of the highest importance. This element plays an essential part in the human body, where it exists in ponderable quantities (3 grammes in a 70-kilogramme body). It is a constituent of haemoglobin in the blood, and is also accumulated by the liver and the spleen.

The amounts of radioactive iron formed by H-bombs with their high neutron fluxes must have been considerable, since large amounts of this metal were used in the shells of the bombs and

were present in their immediate vicinity, whether they were exploded on the tops of towers which were vaporized by the thermonuclear heat, or whether they were exploded on barges which met the same fate.[1] Tons of iron (moreover mixed with manganese and chrome in certain alloys) were thus subjected to the action of neutrons in these explosions, and mixed after vaporization with radioactive fission products and other isotopes present in the original fireball.

Three radioisotopes of cobalt have been found in fall-out [**84**, **85**]. They are isotopes 57, 58, and 60.

Cobalt-57. Its half-life is 270 days. It emits three gammas of 0·01 to 0·13 MeV and X-rays.

Cobalt-58. With a half-life of 71 days, this isotope emits a beta plus in 15 per cent. of disintegrations, three gammas of 0·8 to 1·6 MeV, and X-rays.

Cobalt-60. Half-life 5·2 years. It emits, in particular, a beta negative of 0·3 MeV and three gammas of 1·17, 1·33, and 2·16 MeV.

These three isotopes are thus particularly dangerous because of their gamma activity, especially Co-60 whose half-life at five years is long, and whose two gammas of 1·17 and 1·33 MeV are emitted one after the other at each disintegration. This isotope is used in the well-known 'cobalt-bombs' as a radiation source replacing radium in hospitals which treat tumours by gamma therapy.

The danger of ingesting or inhaling cobalt-60 may be somewhat reduced through the fact that its biological half-life is only eight days, while it does not accumulate in the human body if the ingestion was fortuitous. But, unfortunately, the ingestion of cobalt is more or less continuous thanks to fall-out.

Tests [**85**] carried out after the weapons trials of 1956 showed just how large had been the quantity of cobalt formed, especially cobalt-60. These measurements were correlated with Sr-90 levels and showed that at the instant of the explosion there was 27 per cent. Co-60, 4 per cent. Co-57, and 2 per cent. Co-58 compared with Sr-90.

1. Four explosions of the "Castle" series in March–May 1954, and six explosions in "Operation Redwing" in May–July 1956, according to *Probing the Earth with Nuclear Explosives*, by D. T. Griggs and F. Press, UCRL 6013.

If the H-bomb series of 1956 are put at a total of 15 megatons, this would give 1000 kilogrammes of fission products, including 35 kilogrammes of Sr-90, and about 10 kilogrammes of cobalt-60, which is an enormous quantity.

The report stresses that the proportion between the gamma energy of the cobalt created each second, and the gamma energy of other fission products, must rise considerably for a few years. From 31 per cent. after 1·2 years, it rises to 149 per cent. after 2·6 years, 211 per cent. after 5·6, declining thereafter to 26 per cent after 25·7 years. In these conditions, gamma activity of fall-out must peak several years after the tests, which may explain the observations made of high gamma activities in soils in England [**86**] during 1959.

As for biological concentration, some work was done on shellfish collected near the shore of Rongelap Island (Marshalls) after the 1954 Bikini H-tests.

The quantity of Co-60 formed in this series appears to have been much smaller than in the next—1956. But there was some, nevertheless, and certain species of shellfish accumulated it. Tests were made on a variety of clam (*Tridacna gigas*) in which the gamma from cobalt-60 was found to be between 63 per cent. and 85 per cent. of the total gamma activity.

A first specimen made up of 1·8 kilogrammes of the flesh of these clams gave a count of 2400 gamma disintegrations per second, of which 1500 were from cobalt-60 alone. Another specimen, of 882 grammes, was still more active at 6000 disintegrations per second due to total fission product and cobalt activity, the latter accounting for 5000 disintegrations per second.

This illustrates the unforeseeable migration of radioactivity and the dramatic role played by biological selection and accumulation. Work of a similar nature done at Eniwetok [**85**] proved that six weeks after an explosion 29 per cent. of radioactivity in plankton could be traced to the principal gamma emitters among the fission products and 71 per cent. from isotopes previously ignored: Zn-65; Co-57, 58, and 60; Fe-55 and Mn-54.

Tungsten-185. This isotope, used as a tracer (Chapter 15), was also accumulated in large amounts by the plankton around the test areas, representing 83 per cent. of total activity.

The livers of non-carnivorous fishes contained Zn-65; Co-57, 58, 60; Fe-55; and Mn-54. In their flesh there was more Zn-65 and

Fe-55 than cobalt. In the organs and the tissues of carnivorous fishes there was a marked predominance of Fe-55 and Zn-65.

Disseminated Plutonium-239

Among the very numerous radioactive elements dispersed by a fission bomb is, of course, the unexploded portion of the charge.

We know that the yield of the nuclear explosive is far from perfect; it is nothing like 100 per cent., but probably between 5 and 30 per cent. according to the various techniques which were perfected in so many experiments between 1945 and 1954. In particular, it was reported that the series of three explosions in 1948 at Eniwetok (operation "Sandstone") had made possible a considerable increase in the yield from standard bombs such as those used at Alamogordo, Hiroshima, Nagasaki, and Bikini, 1946.

The critical mass, we have seen, depends on the geometry of the nuclear charge, on its nature, and especially on the nature and thickness of the reflector. For plutonium-239, this critical mass is about five kilogrammes with the best reflector, and 16 kilogrammes unreflected. The energy of the nominal bombs—20 kilotons—represents the complete fission of one kilogramme of fissionable material. In consequence, even in the detonation of the most highly perfected weapon yielding 60 kilotons (bombs at Eniwetok, 1948?), and using a quantity of plutonium close to the minimum possible of about seven kilogrammes, more than half the charge would still not be used in the chain reaction. This residue, vaporized and dispersed in the fireball, is mixed with the three kilogrammes of fission products formed. The energy released would not represent—according to the Einstein formula —a loss of more than a few grammes (1 gramme for 20 kilotons), and this does not really come into calculations which are made only to give orders of magnitude.

From the less perfected bombs, such as those of the first years, hundreds of kilogrammes were added to the inventory of radioactive materials. In the case of the H-bombs using fission detonators the amount of the charge and its efficiency are unknown.

The Effects of Plutonium

Plutonium is a radioactive element whose biological effects are particularly feared, since it is a bone-seeker and emits an alpha particle whose ionizing effects are all the more intense since

its penetration in living matter is shallow (a few thousandths of a millimetre). The half-life of Pu-239 is 24,300 years, and this immense span of time must go by before half the plutonium dispersed throughout the world has disintegrated. In 50,000 years one-quarter will still subsist, while in 100,000 years there will still be one-sixteenth. The decay product is uranium-235, which is also a nuclear explosive, and also was disseminated abundantly in the atmosphere by A-bombs in which only part of the charge was effectively exploded (see notes farther on).

The three main energies of the alpha activity emitted by plutonium-239 are 5·15 MeV (72 per cent.); 5·13 MeV (17 per cent.); and 5·10 MeV (10 per cent.). Several gammas are given off by the excited nuclei of U-235, which are the decay products. The two main ones have energies between 0·01 MeV and 0·05 MeV, and the others are very weak.

The activity—that is, the number of disintegrations of a given quantity of plutonium—is, of course, low, because of the long half-life. For equal amounts it is 15·5 times smaller than that of radium ($24{,}300 = 15{\cdot}5 \times 1600$ and 1600 years is the half-life of radium-226). As 1 gramme of radium emits 37,000,000,000 particles per second—the curie—it is easy to calculate for instance the number of disintegrations in a millionth of a gramme of Pu-239. The answer is 2400 per second.

A priori, this microgramme of plutonium appears ridiculously small, but where radioactivity is concerned, normal everyday experience cannot be relied on, as we have seen at many points in this book. Official figures [**82**] indicate that the maximum amount which may be tolerated for the whole skeleton is 0·04 microcuries of plutonium. This means that not more than three-quarters of a microgramme may be ingested and fixed in bone. For the lungs, the dose is five times less, and not more than one-tenth of a microgramme, giving 500 disintegrations per second, may be inhaled.

This being said, it is easy to understand why, from 1945 onward, scientists have wanted to know what has become of the plutonium being dispersed to the four winds.

Japanese Measurements at Nagasaki

Very little work has been published on the plutonium detection question, and it has often been stated that the most sensitive

measurements were not capable of detecting alpha emitters in fall-out.

Nevertheless, two pieces of research will guide us in the appreciation of this problem.

The first dealt with the presence of plutonium around Nagasaki in samples of soil taken by Japanese physicists. This work [87] is not conclusive. It did not detect ponderable quantities, and did not even prove that the earth and plant samples really contained plutonium. Nevertheless there is a strong presumption in its favour, for technical reasons. The report said that after the explosion of August 9, 1945, at Nagasaki, a village lying 1½ miles to the east was heavily contaminated by radioactivity. This was almost certainly due to rain which fell at that moment and brought down to the ground the remains of the mushroom cloud. Samples of soil and plant roots were taken on the spot, and a Professor Kimura made the analyses. There were fission products of fairly short half-lives and thus of high activities: Sr-89; Ba-140; Ce-144; Zr-95.

In 1951 the same samples were again analysed, the time-lag of six years having permitted the disappearance of short-lived isotopes. There remained only well-known activities of long half-life isotopes: Sr-90 and Cs-137, but also Ce-144 (280 days). For the last it is interesting to note that six years saw eight half-lives go by, so that the activity of cerium-144 was only 1/256, say four-thousandths, of the original level. It was still detectable. Among the long-lived isotopes, analysis showed the presence of an alpha emitter of very long half-life. There is thus good reason to presume it was plutonium, although it was not formally identified.

Dispersion of Pu-239 after the First Explosion

Similar research in the U.S.A. on the other hand supplied very interesting numerical data. The report [88] analysed the distribution of plutonium in the soils of central and north-eastern New Mexico.

The first nuclear explosion of all took place, as we know, on July 16, 1945, at a place called Alamogordo, in the State of New Mexico. It was the famous "Trinity" test. The bomb, fixed at the summit of a metallic tower which was vaporized, had a plutonium charge. The tower was too low to prevent the fireball

from reaching the ground. A shallow crater was formed, and the sand was vitrified in a radius of 600 yards [89]. The amount of sand which was melted by a temperature which exceeded 1400°C was 1700 tons. The thermal energy which produced this effect was 4×10^{19} ergs [89], and represented one-twentieth of the total energy set free by the explosion, which was 8×10^{20} ergs.

Since the fireball touched the soil, a fraction of its contents was mixed with the melted sand. There must thus be some plutonium in this calcined material to which the specialists have given the name of "Trinitite." On the other hand, there is a rapid fall-out of dusts of coarser grain than those carried around the world by the wind, and the mushroom cloud leaves a track on the ground as a result. This track can be detected for years.

The report in question gives details of the tests carried out in New Mexico along the track of "Trinity." This had been delimited at an earlier date by measurements of fission product activity between 1947 and 1956. However, instead of concentrating on fission products, the chemists followed the track through plutonium detection, which represents a considerable technical achievement in view of the minute amounts on which they had to work.

The main results were as follows:

Around the base of the pylon in the crater of vitrified sand, in a radius up to 55 yards, the glassy beads had a plutonium content between 2 and 3 microgrammes per gramme of sand, which is extremely high. In a wider band between 65 yards and 220 yards from the tower the content per gramme of Trinitite was 70 to 80 thousandths of a microgramme of plutonium.

As for the track—about 3 miles wide—which is apparently the trace left on the ground by the radioactive cloud, plutonium was found in the soil between 1 and only 3 centimetres deep. It was detectable at 87½ miles from the test site (still towards the north-east, which indicates the direction of the wind on the fateful July 16, at 5 o'clock). The content was around 0·7 microgrammes per square metre of soil. Maximum soil contamination was found 37½ miles from the site with 14 microgrammes per square yard. At this point, the average over 1·16 square miles was around 8 microgrammes per square yard at a depth of 2 centimetres.

The report said that in 1948 it had been estimated that rapid fall-out had contaminated a total area of 1120 square miles, but the more recent measurements had shown that this figure was too low and that the area was much larger.

Figures were also given on plutonium absorption by pine-trees and by grass.

In pines, the activity of the wood in 1951 was almost undetectable, and measured content very much less than a micro-microgramme of plutonium per gramme of wood. On the other hand, bark and needles had contents between 10 and 50 times higher, although still infinitesimal at 2 to 12 micromicrogrammes for the needles, and 10 to 80 for the bark. The same result was found for grass, showing that plutonium was present at the surface of contaminated objects, as it was practically at the surface of the soil. The desert areas of New Mexico where the explosion took place have little rainfall. But, where any had occurred, there was some displacement of the plutonium layer with erosion, between 1948 and 1956. Such is the gist of this scientific report.

From these data, it is possible to make a very rough but perfectly valid estimate[2] of the quantity of plutonium which has been disseminated. Around the tower in a radius of 55 yards there would be between 100 and 200 grammes, and in a radius of 330 yards about one kilogramme. On the band of earth 3 miles wide and 124 miles long, a mean of 2 grammes per square kilometre gives 2 kilogrammes. Part of the original explosive charge is thus found in the soil in the immediate surroundings of the explosion and along the track of the radioactive cloud. The remainder has, of course, been carried to fall much farther and much more slowly, becoming highly diluted as is normally the case with fall-out.

Dispersion of Uranium-233 and Uranium-235

All the foregoing on plutonium-239 is, of course, valid for the two other fissionable isotopes, U-233 and U-235.

Bombs based on U-233, we saw in Chapter 3, cannot have been very numerous as this isotope is synthesized in reactors by irradiation of thorium-232, which captures a neutron. The advantage of U-233 as an explosive is its low critical mass, equivalent to that of plutonium-239 [1], and the fact that in

2. By the author.

metallic form it is much easier to work than plutonium, which has fantastic and disconcerting physical properties.

Uranium-233. This has a 162,000-year half-life, and emits six alpha-particles. The three most energetic are: 4·82 MeV (83 per cent.), 4·77 MeV (15 per cent.), 4·72 MeV (1·6 per cent.). Three gammas have been detected: 0·1, 0·05, and 0·04 MeV.

The maximum permitted activity in the human body and skeleton is the same as for plutonium, but since the activity of U-233 is about one-seventh that of Pu-239, the maximum body burden will be about seven times that of this isotope.

Uranium-235. This is the explosive that was used for a large number of bombs in the form (Chapter 4) of oralloy. As the critical mass [1] is three times that for Pu-239 and U-233, the amounts dispersed are much larger than in the case of bombs using the latter. A 20-kiloton bomb might contain between 14 and 45 kilogrammes of U-235 and would disintegrate only one kilogramme. Even supposing the bomb were a perfected 60-kiloton device, using only the minimum of explosive (14 kilogrammes), 11 kilogrammes would not enter into the chain reaction, and would be dispersed.

The quantities of U-235 spread around the world between 1945 and 1958 by the radioactive detonation clouds must be high: several hundred kilogrammes.

The tolerance levels for U-235 [82] are the same as for Pu-239 and U-233 for the whole body and slightly higher for the whole skeleton (weighing 7 kilogrammes) at 0·06 microcuries.

U-235 emits seven alphas with energies between 4·12 and 4·56 MeV, and several gammas from 0·1 to 0·4 MeV. But the half-life of U-235 is very long: 710,000,000 years. Thus its activity is very low; 300,000 times lower than plutonium.

The danger from the dispersion of U-235 is, consequently, very limited, and far less than that from plutonium. It would only be of consequence if there were a concentration into plaques of high intensity, or if edible plants or organisms accumulated it.

Transuranic Elements

Special reference must be made to the presence of the transuranic elements in fall-out. This subject was broached above with plutonium. But this is an entirely different case, involving

the synthesis of these isotopes in large quantities by the explosion of fission-fusion-fission bombs using thorium and, especially, natural uranium reflectors. Successive neutron captures in the isotopes Th-232 and U-238 are responsible for their appearance.[3]

In the case of U-238, the first thermonuclear explosion ("Mike," November 1, 1960) synthesized up to fermium, element number 100 of the table, which was detected later in analyses of the coralline debris from the explosion.

Calculations[4] show that the isotopes Pu-239, Pu-240, and the long-lived doublet Pu-241/Am-241 are formed in appreciable amounts.

From a 10-megaton bomb:

Plutonium-239. In each such bomb about 70 kilogrammes is produced by neutron capture of U-238, yielding U-239 (half-life 23 minutes), which decays to neptunium-239 (half-life 2·3 days), and then to plutonium-239. The number of explosions of fission-fusion-fission bombs in 1954, 1956, and 1958 probably have more than doubled the amount of Pu-239 from the residues of A-bomb charges indicated on p. 206. This plutonium, like the isotopes below, has been blasted into the stratosphere. This makes it all the more to be feared because of its homogeneous deposition at some later stage.

Plutonium-240. About 5 kilogrammes of this isotope is synthesized in a 10-megaton bomb, bringing total content of fall-out to some tens of kilos. This isotope is more dangerous even than Pu-239. Its half-life is 6500 years, and its activity is four times higher for equal amounts. Thus the biologically acceptable weight is four times less.

Plutonium-241. This is very dangerous to life because it has a 13-year half-life, and decays by beta negative emission to americium-241 of 470 years half-life. This last emits a group of alphas around 5·4 MeV and about 10 gammas. The biological half-life of this doublet is, however, much shorter than for Pu-239 and Pu-240 [82]. A 10-megaton bomb would synthesize about 300 grammes of Pu-241, equivalent to a total of at least two kilogrammes in the whole mass of fall-out.

Neptunium-237. This results from the (n, $2n$) reaction on U-238, which becomes U-237 (half-life, 6·7 days) and after

3. See table on p. 219. 4. Author's work (1955).

beta negative emission neptunium-237. Japanese physicists detected and measured U-237 in large amounts in ash from Bikini in March 1954 ([41], p. 497). Here again calculations show that about 40 kilogrammes are produced per 10 megatons. The presence of hundreds of kilos of Np-237 in worldwide fall-out is a certainty. Its half-life is 2,200,000 years. It emits a group of alphas around 4·8 MeV and several gammas.

These isotopes are the main ones which should be mentioned since they are the most abundant. Detection work done on the alpha emitters to date shows that they are very difficult to isolate for technical reasons. Their intrinsic activity is weak because of their long half-lives and especially because they are drowned in a background of much greater activities from fission products which are beta and gamma emitters. They are nonetheless present and all the more insidious because of their chemical characteristics, which make them bone-seekers. Moreover, their alpha particles have an ionizing effect twenty times higher [82] than that of beta or gamma, and that along a very short path in organic tissue.

To all this must be added the fact which is never stressed, although it is of capital importance, that ALL these isotopes are present simultaneously in living things with all the fission products and the other isotopes mentioned in this chapter. Their biological effect is, of necessity, cumulative, although it is not known whether their effects should be added or multiplied together.

Chemical Effects of Explosions

There is, finally, a series of effects of nuclear explosions which must be recorded and which should be the subject of more research, especially on the experimental plane. It is the formation of a wide range of exceptional chemical compounds made possible by the physics of nuclear explosions (thermal and ionizing effects). Many of these compounds may be synthesized in very large amounts and be disseminated with fall-out.

Lithium has been detected at very high altitude [90, 91]. It is probably of human origin, projected into the stratosphere by H-bombs, a fraction of whose charge must include an isotope of this element.

It may be that other elements such as boron or the very

poisonous beryllium are also included in the initial charges of composite bombs.

Extremely harmful chemicals can be formed by reactions between the numerous elements present at the moment of an explosion: light elements from the H-bombs, the range of fission products, heavy elements (thorium to californium), those obtained by neutron activation, the metals from the mechanisms and ancillary objects, elements torn from the earth and from coral reefs, and the oxygen and nitrogen of the air.

The complexity of chemical reactions during and after an explosion has been described in a recent work on fission products [92].

Nitrous compounds and nitric acid formed in large quantities by thermal effects on the air must not be forgotten. The characteristic reddish tinge of the mushroom clouds is due to their presence. This effect has been analysed in [73].

Research so far has put the accent on the nuclear aspect of fall-out but there is also a chemical effect that cannot be neglected.

PART IV: CONCLUSIONS

Conclusions

Prophets are believed only after the event.
PASCAL

THIS is a summary of the major facts set forth in this book.

1. Nuclear energy offers an incredible potential source of new energy in the form of uranium fission and, doubtless, at a later stage, of controlled thermonuclear fusion.

2. It is already clear that a considerable proportion of the world's electricity and heat needs can be met by means of nuclear reactors. Also, their use in transportation is an accomplished fact and will expand enormously.

3. The use of radioisotopes is by far the most promising field, both for pure research (tracers) and for the innumerable applications that are possible in many branches of industry, chemical processing, and medicine.

4. Nuclear science is fundamental—at the basis of all things —since atoms are the units out of which every piece of matter is made. Thus we will draw from this 'elementary' science so many new and as yet unsuspected discoveries that present prospects will appear quite puny in the eyes of our descendants a few decades hence.

5. Nuclear energy was first used in military applications and progress since then has so far been mostly along these lines. The energy set free between 1945 and 1961 by nuclear explosions alone is much superior to the 'peaceful' energy released up to the 1960's.

6. Nuclear fission entails the creation of radioisotopes, some of which have a long half-life. The bombs have produced these fission products, and several tons have been spread over the whole of the earth's surface.

7. Nuclear industries also produce these radioisotopes, and chemical treatment of irradiated uranium requires the storage of large quantities of radioactive wastes and the disposal of a small, but increasing, amount in the sea or underground.

8. Fall-out from explosions; low-level radioactive wastes released to air, to the waters of rivers and of the sea; nuclear accidents (power-plants and ships); stored wastes which could accidentally be released; and the increasing uses of radioisotopes are the many causes of an inevitable rise in both local and general levels of activity.

9. On average, external irradiation due to this activity will be low; it could be high locally.

10. Biological accumulation—selective extraction—is on the other hand to be feared. This has already been proved by the consequences of fall-out and some examples of natural biological cycles near atomic energy sites.

11. The deposition of fall-out is not as homogeneous as was first believed. Measurements are reduced to averages, but the spread on each side of the actual results is broad, both for areas widely separated on the earth's surface, and for areas in the same region. Rainfall, altitude, the nature of the soil, and the latitude bring wide variations in the amount of fall-out, as well as biological accumulation by plants and animals.

12. Marine contamination is an even more delicate matter, since the sea favours the dissemination of radioisotopes and their transfer between living things.

13. All living things on earth—man included—are impregnated with artificial radioactive isotopes as a result of breathing and taking in water and food.

14. A table can be drawn up of the quantities of the principal radioactive isotopes synthesized by all nuclear explosions between 1945 and 1958. This list is obviously only an estimate and contains only orders of magnitude. The exact figures are not possible to establish for various reasons: lack of knowledge of the energy released by each explosion, of the exact number of explosions, and, especially, of the mechanisms and compositions of the weapons.

This table summarizes figures encountered in this book. Those for the fission products are based on the estimate that 90 megatons of fission energy has been released (p. 127) and that about 5 tons of fission products have been created. The quantity of each isotope is deduced from the percentage of yield given in Fig. 6*a* (p. 57). Not all the radioisotopes formed in explosions are here, only those with a half-life of, or more than, six months.

The symbol *n* indicates a figure between 2 and 9. For example, *n* × 100 grammes means between 200 and 900 grammes.

Isotope	*Half-life*	*Amount Synthesized*
H–3 (Tritium)	12 years	30 kg
C–14	5600 years	600 kg
Ca–45	6 months	*n* × 100 grammes
Mn–45	10 months	*n* × 10 grammes
Fe–55	2·6 years	*n* × 100 kg
Fe–60	300,000 years	*n* grammes
Co–57	9 months	10 kg
Co–60	5·2 years	50–100 kg
Ni–63	100 years	*n* × 10 grammes
Zn–65	8 months	*n* × 100 grammes
Rh–102	7 months	*n* × 10 grammes
ALL FISSION PRODUCTS		Over 5000 kg
Se–79	60,000 years	2 kg
Kr–85	10·6 years	12 kg
Rb–87	50,000,000,000 years	75 kg
Sr–90	28 years	160 kg
Zr–93	1,000,000 years	275 kg
Tc–99	200,000 years	335 kg
Ru–106	1 year	150 kg
Pd–107	7,000,000 years	50 kg
Cd–113	5 years	2·5 kg
Sn–119	9 months	3 kg
Sn–121	5 years	3 kg
Sb–125	2 years	3·5 kg
I–129	17,000,000 years	50 kg
Cs–135	3,000,000 years	300 kg
Cs–137	33 years	300 kg
Ce–144	10 months	350 kg
Pm–147	2·6 years	150 kg
Sm–151	90 years	75 kg
Eu–155	1·7 years	3·5 kg
U–233	162,000 years	*n* × (10–100) kg
U–235	710,000,000 years	*n* × 100 kg
Natural uranium (mainly U–238)		*n* × 10,000 kg
Np–237	2,200,000 years	400 kg
Pu–239	24,300 years	Over 1000 kg
Pu–240	6500 years	50–100 kg
Pu–241/Am–241	13 years–470 years	3 kg
Pu–242	380,000 years	100–200 grammes
Am–243	8000 years	*n* grammes

15. Altogether, nuclear explosions must have synthesized some 10,000 kilogrammes of radioisotopes which did not exist before. Of these, about forty have a long half-life.

This language is perhaps not very eloquent for the layman, but for the atomic physicist it is horrifying. It can be made more comprehensible if it is known that the amounts of radioisotopes used in the laboratory are almost always less than one-millionth

of a gramme, exceptionally a milligramme. In the case of radium, better known by the general public, the use of one gramme necessitates an astonishing number of precautions. Since its discovery by Marie Curie, more than sixty years ago, total world production of radium has not yet reached one kilogramme.

We know, on the other hand, that just one microgramme of plutonium-239 fixed by the bones of a human being is fatal. But in 1000 kilogrammes there are a million million microgrammes. The quantity of plutonium dispersed to the four winds by nuclear explosions is thus enough to be fatal to a million million human beings if it were integrally disseminated and ingested. This will, of course, not take place because of the fixing of much of this material in the seas, the deserts, and all the ground which does not participate in the production of human food.

A parallel to this is the production in each city every day by cars running through its streets of enough carbon monoxide to kill every inhabitant. But for this each exhaust pipe would have to be put to the face of each inhabitant. In reality, the city-dwellers breathe only a tiny fraction of the exhaust gases, and this dose is not mortal. The same applies to the 10 tons of fall-out spread around the world. They represent a frightful destructive potential for all living things and for humanity, but their cumulative effects are greatly reduced because of extreme dilution.

However, whether this dilution is sufficient, and especially whether biological accumulation could not offset it to a point of grave danger, biologists must judge. Only the future will give us the correct answer.

One point must be stressed, that of the permanence of some of these radioactive biological poisons.

Because of its half-life, most of the 1000 kilogrammes of plutonium-239 will still be in existence 100, 1000, and even 10,000 years hence. That which has been created and disseminated, and will be if war should break out, will continue to exist and enter into vital cycles all over the earth during the next few thousand years.

16. Not merely one isotope, nor yet a few, has penetrated the life-cycles of the world. Many isotopes have done this simultaneously. Metabolic functions operate on this group of substances, concentrating some and rejecting others.

This major fact must not be forgotten for one moment, because

all the concepts of tolerance and maximum permitted dose are continuously applied to a single radioisotope whose effects on animals are studied in the laboratory. Yet it is on a global scale that plants, animals, and men are impregnated, not only by fission products but also by all the other radioisotopes formed by bombs. These isotopes have widely differing half-lives, radiation energies, and chemical and biological functions, which multiplies the probability that several will be especially harmful—the others being dangerous to different degrees.

These are the established and irrefutable facts. As to the consequences which must be expected, I stated in the preface that I could not go into this aspect as I am a theoretical physicist and not a specialist in living things—biologist, geneticist, or doctor. The best I can do is to quote an opinion from one authority whose common sense and humanity are obvious. This is an open letter by Professor Albert Szent-Györgyi, of the United States Institute of Muscular Research, Nobel Prize winner for Physiology and Medicine, to the *New York Times* on March 31, 1958.[1]

> Whether or not radioactive fall-out will probably reach the maximum tolerance level is a question which is being discussed everywhere. I wish to point out that we do not know where this level is. The most important experiments in this area have been made on mice or on *Drosophila*. If they are correctly carried out over a long period of time they will be able to yield an exact answer as to the permitted limits for mice or *Drosophila*, but this will have no validity for man, quite simply because man is neither a mouse nor a fly.
>
> No one can be more convinced than I am as to the unity of all living things and, as I have often pointed out, there is no fundamental difference between cabbages and kings. But this belongs to basic principles and not to the more subtle biological reactions involved in the problems of health and disease in man.
>
> I also wish to underline a fallacious aspect of statistics. If, for example, cases of leukaemia were to go up by a small fraction, say 0·1 per cent., this may appear really insignificant. But 0·1 per cent. can mean 1500 cases spread over the whole population. Fifteen hundred dead children laid side by side would look somewhat different from the figure 0·1 per cent. and I believe that if the children of those who think 0·1 per cent. is insignificant were among the 1500, they would arrive at a different evaluation.

1. *New York Times*, International Edition, April 17, 1958.

> I know that those who fashion national policies must weigh one chance against another and place in the scales this 0·1 per cent. against the millions of lives lost in a possible war. But it may be that human intelligence will be able to find a road to peace which does not have to pass over children's corpses.

Apparent knowledge characterizes the false scientist, and humility the true one who does not fear to admit beforehand his ignorance of the results of an experiment.

But since 1945 a vast experiment has been in progress, that of the effects of disseminated radioactivity. The whole earth is its laboratory, all men, women, and children are its guinea-pigs.

References

1. "Critical Masses of Oralloy Assemblies," GLEN A. GRAVES AND H. C. PAXTON, Los Alamos Scientific Laboratory, *Nucleonics*, vol. 15 (June 1957), p. 90.

2. The relative yields of fission products in function of the isotope undergoing fission (U-235, U-238, Pu-239, Th-232) and in function of the energies of the incident neutrons are given in the five graphs on pp. 56 and 57. They are based on the references below as follows:

Fig. 5*a* is based on 3 and 4.

Fig. 5*b* is based on 6 (U-235) and 4 (Pu-239).

Fig. 6*a* is based on 4 and 5.

Fig. 6*b* is based on 4, 5, and 6.

Fig. 6*c* is based on 6.

3. *Accumulation of Fission Products from U-235*, A. K. BOOTH and D. SCHWEITZER. Document BNL 407 (T-78) Brookhaven National Laboratory, (July, 1956).

4. "Fission-Product Yields from U, Th, and Pu," SEYMOUR KATCOFF, Brookhaven National Laboratory, *Nucleonics*, vol. 16 (April, 1958).

5. "Survey of Radiochemical Studies of the Fission Process," E. P. STEINBERG and L. E. GLENDENIN, Argonne National Laboratory. Document P/614 of the first Geneva Conference, *Peaceful Uses of Atomic Energy*, United Nations, vol. 7 (1956).

6. *The Fission-Process Mechanisms and Data*, R. B. LEACHMAN, Los Alamos Scientific Laboratory. Document P/2467 of the second Geneva Conference.

7. "Table of Isotopes," D. STROMINGER, J. M. HOLLANDER, G. T. SEABORG, *Reviews of Modern Physics*, vol. 30 (April 1958), p. 585.

8. *Nuclear Explosions and their Effects* (*Chart Id*). The Publication Division, Ministry of Information and Broadcasting, Government of India (1958).

9. *The Development of Atomic Energy and its Industrial Applications.* U.K. White Paper 1960 on Nuclear Power Programme. Lecture by Sir Christopher Hinton, Chairman, Central Electricity Generating Board, to the Trades Union Congress Conference on Radiation in Industry, October 13, 1960.

The U.K. Programme for the Development of Nuclear Power, W. STRATH, United Kingdom Atomic Energy Authority. Document P/262 of the second Geneva Conference.

10. *The Swedish Nuclear Energy Programme*, GUSTAV CEDERWALL. Document P/2342 of the second Geneva Conference.

11. *Nucleonics*, vol. 17 (December 1959), p. 24.

12. *Nucleonics*, vol. 17 (May 1959), p. 166.

13. "How we developed the Nautilus Machinery," Commander E. E. KINTNER, Nuclear Power Superintendent, Mare Island Naval Shipyard, California, *New Scientist*, vol. 5 (March 26, 1959), p. 694.

14. "Navy Makes Great Strides," JOHN E. KENTON, *Nucleonics*, vol. 17 (September 1959), p. 73.

15. "Atomnyi Liodokol" (The Atomic Ice-breaker), IOU I. KLIMOV, *Pravda* (Moscow), Number 12 of 1959, p. 35.

16. *Discovery* (November 1959), p. 466.

17. *Nature*, vol. 184 (September 5, 1959).

18. *New York Times*, International Edition (July 26, 1959).

19. *Nucleonics*, vol. 17 (June 1959), p. 96.

20. *Non-Military Uses of Nuclear Explosions*, H. BROWN and G. W. JOHNSON, University of California Radiation Laboratory. Document P/2179 of the second Geneva Conference.

21. "Slow-Neutron-Induced Activities," C. E. MANDEVILLE, *Nucleonics*, vol. 9 (November 1951), p. C-8.

22. *Radioactivity in Terrestrial Animals Near an Atomic Energy Site*, W. C. HANSON and H. A. KORNBERG, General Electric Company, U.S.A. Document P/281 of the first Geneva Conference.

23. "Zinc-65 in Food and People," R. W. PERKINS and J. M. NIELSEN, General Electric Company, U.S.A., *Science*, vol. 129 (January 9, 1959), p. 94.

24. *Studies of Radioactivity in Fish from White Oak Lake and the Clinch River*, V. I. KNOBF, Oak Ridge, National Laboratory. Document ORNL 1031, U.S. Atomic Energy Commission, unclassified (July 9, 1951).

25. *Science*, vol. 124 (July 6, 1956), p. 17.

26. *Disposal of Radioactive Waste*, K. SADDINGTON and W. L. TEMPLETON, George Newnes Limited (London, 1958).

27. *Origins and Nature of Radioactive Wastes*, F. R. BRUCE, Oak Ridge National Laboratory. Scientific conference on the disposal of radioactive wastes, Monaco, November 16–21, 1959.

28. *Packing of Radioactive Waste for Sea Disposal and the Protection of Fisheries Operating off Canada's Pacific Coast*, MICHAEL WALDICHUK, Fisheries Research Board of Canada. Scientific conference on the disposal of radioactive wastes, Monaco, November 16–21, 1959.

29. "The Accident at Windscale," *Nature*, vol. 182 (September 6, 1958), p. 635.

30. *District Surveys Following the Windscale Accident*. Document P/316 of the second Geneva Conference.

31. *Discovery* (December 1958), p. 520, quoting P. A. Sheppard, Professor of Meteorology at Imperial College, London.

32. "Long-Range Travel of the Radioactive Cloud from the Accident at Windscale," N. G. STEWARD and R. N. CROOKS, U.K. Atomic Energy Establishment, Harwell, *Nature*, vol. 182 (September 6, 1958), p. 627.

33. "Iodine-131 in Sheep before and after a Nuclear Reactor Accident," L. VAN MIDDLESWORTH, University of Tennessee, *Nature*, vol. 181 (January 25, 1958), p. 256.

34. *International Aspects of Radioactive Contamination in Western Europe and the Necessity of International Control Arising from It*, Royal Netherlands Academy of Science. Document P/2425 of the second Geneva Conference.

35. "It's Time to Look at Nuclear Merchant Ship Safety," R. A. FARRAM and H. S. SCHENIDER, Aerojet-General Nucleonics, U.S.A., *Nucleonics*, vol. 15 (May 1957), p. 109.

36. "The Safety of Nuclear Reactors," C. R. MCCULLOUGH, M. M. MILLS, E. TELLER, *Peaceful Uses of Atomic Energy*, vol. 13 (1956), p. 79.

37. "Small A-Weapons Tested by the U.S.," *New York Times*, International Edition, March 12, 1959.

38. *New York Herald Tribune*, Paris, November 8–9, 1958.

39. Large extracts from this report were published in the *New York Times*, International Edition, August 25, 1959.

40. *The Nature of Radioactive Fall-Out and its Effects on Man.* Hearings before the Special Sub-committee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, Parts I and II (1957).

41. *Research on the Effects and Influences of the Nuclear Bomb Test Explosions*, by the Committee for the Compilation of a Report on Research in the Effects of Radioactivity. Japan Society for the Promotion of Science, Ueno-Toyko (1956).

42. *The Effects of High-Yield Nuclear Explosions.* Statement by LEWIS L. STRAUSS, Chairman, and a report by the United States Atomic Energy Commission, February 1955.

43. *Radioactive Fall-out in North America from Operation "Teapot,"* ROBERT J. LIST, Weather Bureau, Washington. Document NYO 4696 (Del), U.S. Atomic Energy Commission (February, 1956).

44. "Atmospheric Aspects of Strontium-90 Fall-out," E. A. MARTELL, U.S. Air Force Cambridge Research Center, *Science*, vol. 129 (May 1, 1959), p. 1197.

45. "Radioactive Ashes over Calcutta and a Method of Dating a Nuclear Explosion," DR SANTIMAY CHATTERJEE, Institute of Nuclear Physics, Calcutta, *Atomic Scientists Journal*, vol. 4 (May 1955), p. 273.

46. "The Circulation of Radioactive Isotopes," JAMES R. ARNOLD and E. A. MARTELL, *Scientific American* (September 1959), p. 85.

47. "Contamination of the Air by Radioactivity from the 1958 Nuclear Tests in the Pacific," L. B. LOCKHARDT JR., R. A. BAUS, R. L. PATTERSON JR., A. W. SAUNDERS JR., U.S. Naval Research Laboratory, Washington, *Science*, vol. 130 (July 17, 1959), p. 161.

48. A.F.P.-A.P. New York, July 29, 1958. *Le Monde*, July 30, 1958.

49. "Ratio of Caesium-137 and Strontium-90 Radioactivity in Soil," P. F. GUSTAFSON, Argonne National Laboratory, *Science*, vol. 130 (November 20, 1959), p. 1404.

50. "Caesium-137 in Swedish Milk and Soil," K. Löw and K. EDVARSON, Research Institute of National Defence, Stockholm, *Nature*, vol. 183 (April, 18 1959), p. 1505.

51. "Gamma Radiation from Deposited Fall-out," D. H. PEIRSON and L. SALMON, U.K. Atomic Energy Research Establishment, Harwell, *Nature*, vol. 184 (November 28, 1959), p. 1678.

52. "Deposition of Sr-90 through October 1958," MERRIL EISENBUD, *Science*, vol. 130 (July 10, 1959), p. 76.

53. "Natural and Fission-Produced Gamma-Ray Emitting Radioactivity in Soil," P. F. GUSTAFSON, L. D. MARINELLI, S. S. BRAR, Argonne National Laboratory, *Science*, vol. 127 (May 23, 1958), p. 1242.

54. "*Radioactivnie Vypadenia Poslie Prekrachenia Iadernykh Ispytanyi* (Fall-out after the suspension of nuclear tests)," V. SANTGOLTSER, *Atomnaïa Energia* (Moscow, November 1959), p. 480.

55. "*Radioactivnie Vypadenia V Okrestnostiakh Leningrada* (Fall-out in the Leningrad area)," V. P. CHVEDOV, V. A. BLINOV, L. I. GUEDEONOV, E. P. ANKOUDINOV, *Atomnaïa Energia* (Moscow, November 1958), p. 577.

56. See [81], p. 15.

57. "Biogeochemical Enrichment of Fission Products," PONTUS LJUNGGREN, Geological Institute, Lund, Sweden, *Nature*, vol. 184 (September 19, 1959), p. 912.

58. "The Mystery of Horns and Hormones," *New Scientist*, vol. 6 (July 30, 1959), p. 119.

59. "Fall-out Radioactivity in a Deer's Antlers," J. HAWTHORN and R. B. DUCKWORTH, Royal College of Science and Technology, Glasgow, *Nature*, vol. 182 (November 8, 1958), p. 1294.

60. "Current Strontium-90 Level in Diet in United States," J. LAURENCE KULP and RIETA SLAKTER, Lamont Geological Observatory, Columbia University, *Science*, vol. 128 (July 11, 1958), p. 85.

61. "Caesium-137 in Dried Milk," D. V. BORKER, U.K. Atomic Energy Research Establishment, Harwell, *Nature*, vol. 183 (April 4, 1959), p. 291.

62. "Gamma-Activity of Contemporary Man," C. E. MILLER and L. D. MARINELLI, *Science*, vol. 124 (1956), p. 122.

63. *Strontium-90 in Human Diet in the U.K.* 1959, Agricultural Research Council, Radiobiological Laboratory Report No. 3, H.M.S.O.

64. "Strontium-90 in the Australian Environment 1957–58," DR F. J. BRYANT, U.K. Atomic Energy Establishment, Harwell, and L. J. DWYER, DR J. H. MARTIN and PROF. E. W. TITTERTON, C.M.G., Australian Atomic Weapons Tests Safety Committee, *Nature*, vol. 184 (September 12, 1959), p. 755.

65. "Strontium-90 in Man (III)," J. LAURENCE KULP, ARTHUR R. SCHUBERT, ELIZABETH J. HODGES, Lamont Geological Observatory, Columbia University, *Science*, vol. 129 (May 8, 1959), p. 1249.

66. "Thyroid Radioactivity after Nuclear Weapons Tests," C. L. COMAR, B. F. TRUM, U. S. G. KUHN, R. H. WASSERMAN, M. M. NOLD, J. C. SCHOOLEY, *Science*, vol. 126 (July 5, 1957), p. 16.

67. "Radioactivity in Thyroid Glands Following Nuclear Weapons Tests," L. VAN MIDDLESWORTH, University of Tennessee, *Science*, vol. 123 (June 1, 1956), p. 982.

68. G. M. DUNNING in *Nucleonics*, vol. 14 (February 1956), p. 38.

69. "Radioactive Fission Products in Lungs," T. SCHÖNFELD, K. LIEBSCHER, F. KARL, CHRISTINE FRIEDMAN, First Chemical Institute, University of Vienna, *Nature*, vol. 185 (January, 16, 1960), p. 192.

70. *Continental Water Balance, Ground Water Inventory and Storage Times, Surface Ocean Mixing Rates and World Wide Water Circulation Patterns from Cosmic Ray and Man-Made Tritium*, FRIEDRICH BEGEMANN and W. F. LIBBY, Document 221, Unesco International Conference on Radioisotopes in Scientific Research, 1956.

71. "Growth of the Tritium Content of Atmospheric Molecular Hydrogen," K. F. BISHOP and B. T. TAYLOR, U.K. Atomic Energy Authority, Harwell, *Nature*, vol. 185 (January 2, 1960), p. 26.

72. "Stratospheric Carbon-14, Carbon Dioxide, and Tritium," FRENCH HAGEMANN, JAMES GRAY JR., LESTER MACHTA, ANTHONY TURKEVITCH, *Science*, vol. 130 (September 4, 1959), p. 542.

73. "The Cumulative Effects Caused by Thermonuclear Explosions on Earth," CHARLES-NOËL MARTIN, *Comptes Rendus de l'Academie des Sciences*, vol. 239 (November 15, 1954), p. 1287.

74. *Radiocarbon Dating*, WILLARD F. LIBBY (University of Chicago Press, 1952).

75. "Radiocarbon from Nuclear Tests," WALLACE S. BROECKER, Geology Department, Columbia University, and ALAN WALTON, National Physical Laboratory, Teddington, *Science*, vol. 130 (August 7, 1959), p. 309.

76. *Atmospheric Radiocarbon as a Tracer in Geophysical Circulation Problems*, T. A. RAFTER and G. J. FERGUSSON, Department of Scientific and Industrial Research, Division of Nuclear Sciences, New Zealand. Document P/2128 of the second Geneva Conference.

77. "Studies on the Radioactive Material in the Radiologically Contaminated Fishes Caught in the Pacific Ocean in 1954," M. SAIKI, S. OKANO, T. MORI. *Bull. Japanese Soc. Sci. Fisheries*, vol. 10 (1955), p. 902.

78. "Biological Cycle of Fission Products Considered from Viewpoint of Contamination of Marine Organisms," YOSHIO HIYAMA, University of Tokyo, *Peaceful Uses of Atomic Energy*, vol. 13 (1956), p. 368.

79. "Nuclear Science and Oceanography," R. REVELLE, T. R. FOLSOM, E. D. GOLDBERG, J. D. ISAACS, Scripps Institution on Oceanography, *Peaceful Uses of Atomic Energy*, vol. 13 (1956), p. 371.

80. "Zinc-65 in Foods," G. K. MURPHY, A. S. GOLDIN, J. E. CAMPBELL, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio, *Science*, vol. 130 (November 6, 1959), p. 1255.

81. *Separation and Confirmation of Zinc-65 in the Muscle Tissue of a Skipjack*, K. YAMADA, H. TOZAWA, K. AMANO, A. TAKASE, Preservation Research Division, Tokai Regional Research Laboratory, reference [41], p. 855.

82. *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water*, Handbook No. 52 of the National Bureau of Standards, March 20, 1953, since completed by: *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*, Handbook No. 69 of National Bureau of Standards, June 5, 1959.

83. "Detection of Manganese-54 in Radioactive Fall-out," WILLIAM H. SHIPMAN, PHILIP SIMONE, HERBERT V. WEISS, U.S. Naval Radiological Defense Laboratory, San Francisco, *Science*, vol. 126 (November 8, 1957), p. 971.

84. *Research on Marine Biology at the Eniwetok Atomic Test Centre*, FRANCK G. LOWMAN, Laboratory for Radiation and Biology, Washington University. Monaco Conference, November 16–21, 1959.

85. "Long-lived Cobalt Isotopes Observed in Fall-out," PETER O. STROM, JAMES L. MACKIN, DOUGLAS MACDONALD, PAUL E. ZIGMAN, U.S. Naval Radiological Defense Laboratory, San Francisco, *Science*, vol. 128 (August 22, 1958), p. 417.

86. "Biological Concentration by Killer Clam of Cobalt-60 from Radio-Active Fall-out," HERBERT V. WEISS and WILLIAM H. SHIPMAN, U.S. Naval Radiological Defense Laboratory, San Francisco, *Science*, vol. 125 (April 12, 1957), p. 695.

87. *Radiochemical Interpretation of the Radioactive Fall-out at Nagasaki*, K. KIMURA, E. MINAMI, N. SAITO, Y. SASAKI, N. KOKUBU, University of Tokyo, reference [41], p. 529.

88. *The Distribution of Plutonium in the Soils of Central and North-*

eastern New Mexico as a Result of the Atomic Bomb Test of July 16, 1945, J. H. OLAFSON, H. NISHITA, K. H. LARSON, University of California, Los Angeles Campus, School of Medicine Atomic Energy Project. Document UCLA 406, Biology and Medicine (September 19, 1957).

89. *Thermal Effects of Atomic Bomb Explosions on Soils at Trinity and Eniwetok*, EUGENE STARITZKY, Los Alamos Scientific Laboratory. Document AECD 2881 of the U.S. Atomic Energy Commission (June 13, 1950).

90. *Comptes rendus de l'Academie des Sciences de Paris*, vol. 247 (1958), pp. 806 and 886.

91. "Origin of Upper Atmosphere Lithium Atoms," D. R. BARBER, Norman Lockyer Observatory, University of Exeter, *Nature*, vol. 183 (February 7, 1959), p. 384.

92. "Fractionation Phenomena in Nuclear Weapons Debris," K. EDVARSON, KERSTIN LÖW, and J. SISEFSKY, Research Institute of National Defence, Stockholm, *Nature*, vol. 184 (December 5, 1959), p. 1771.

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